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ABSTRACT

This concept module on work is one of thirteen modules that provide a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, postsecondary technical schools. Each of the thirteen concept modules discusses a single physics concept and how it is applied to each energy system. In this module, work is defined, and various applications of work in the fields of mechanical, fluidal, thermal, and electrical energy are shown. Included with the concept module are eight application modules that discuss a specific application of a single concept in a single energy system, and contain a student laboratory exercise. Laboratory modules included are Work Done on an Elevator, Work Done by a Winch, Work Done by a Water Pump, Work Done by a Hydraulic Lift, Heat Energy Required for a Temperature Increase, Heat Energy Required for Melting, Heat Energy Required for Boiling, and Fundamentals of Air Conditioning. (LRA)

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UTC

UNIFIED TECHNICAL CONCEPTS

CONCEPT MODULE 2-0

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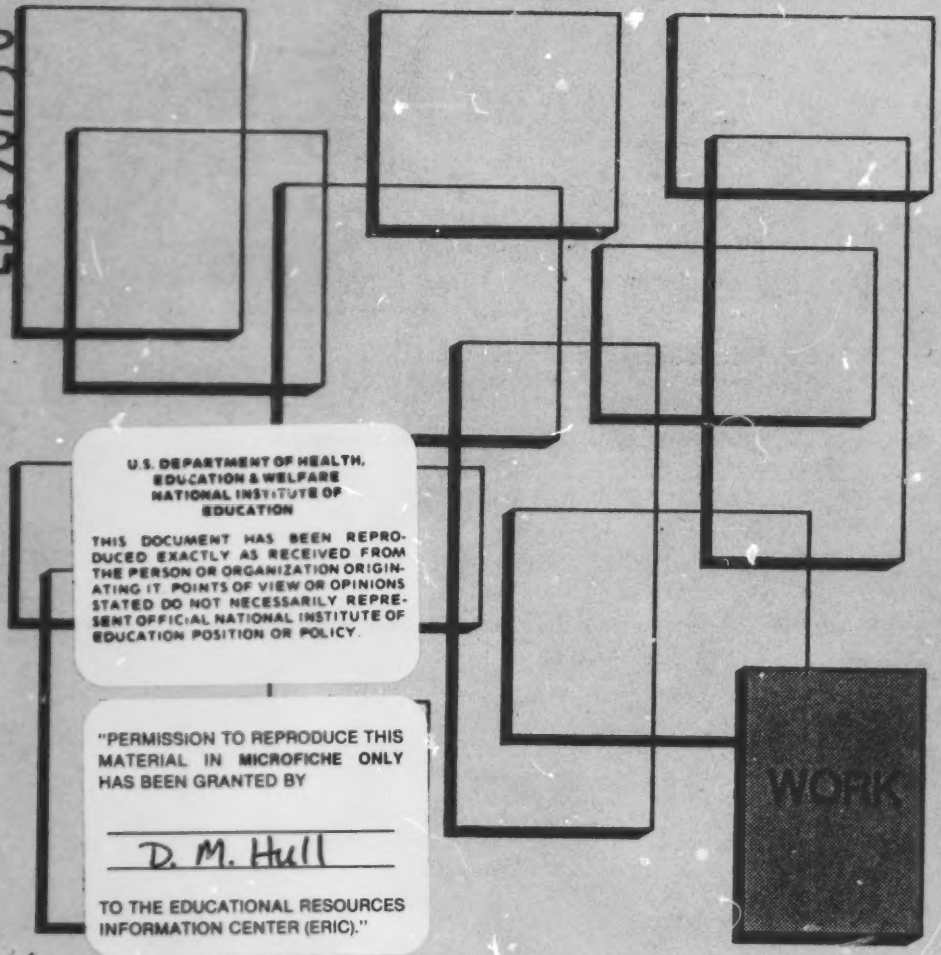
CE 025 469



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INTRODUCTION TO UTC

Complex, modern equipment often contains combinations of hydraulic, pneumatic, thermodynamic or optical subsystems, as well as mechanical and electrical components. These subsystems and components appear not in isolation but as interdependent parts of complex systems. Consequently, a modern technician must understand not only the separate subsystems but also their interrelationships and the roles they play in an integrated system.

Since physics provides the foundation for modern technology, physics instruction in technical programs cannot be overemphasized. Physics courses for technicians should achieve three major objectives:

- Provide students with all the basic physics principles that apply to their chosen field
- Reinforce these principles through the use of "real" examples and hands-on experience.
- Organize knowledge and skills gained in a manner that provides ease of application in solving systems-oriented problems.

These objectives must be accomplished in a minimum of instructional time, and in a manner flexible enough to meet the needs of a variety of technical specialties.

Unified Technical Concepts (UTC) is a flexible, laboratory-based physics instructional package designed to meet the specialized needs of students in two-year, post-secondary technical schools. UTC organizes technical physics into 13 basic concepts (Force, Work, etc.) that apply in four "energy systems" (Mechanical, Fluidal, Electrical, Thermal). Each of the 13 "concept" modules discusses a single physics concept and how it is applied to each energy system. Similarly, each "application" module discusses a specific application of a single concept in a single energy system, and contains a student laboratory exercise.

The recommended prerequisite for UTC is one year of high school algebra, but eight supplementary modules are available for students requiring additional skills or review in the areas of math, units and graphing.

UTC is an alternate method of presenting what heretofore has been a formidable and sometimes confusing subject for technicians. It provides laboratory experiments that apply to specific technological fields, which allows a student to relate more quickly to module content - to understand how it applies to a specific technology.

UTC also represents a unique approach to teaching applied physics. Its flexible modular format allows it to be tailored by physics and technology instructors to meet

specific needs of students in a specific technology.

STRUCTURE OF UTC

The modern world is based on the control and application of energy. Technology is the means by which that energy is applied to accomplish a desired task. Technical physics, being primarily a study of the physical basis of the control and use of energy, can be categorized according to the type of energy involved. Thus, in UTC, physics is divided first into four "energy systems" - Mechanical, Fluidal, Electrical and Thermal.

The same divisions are characteristic of traditional approaches to teaching technical physics. A student usually begins by studying mechanics. Once this branch of physics (energy system) is mastered, electromagnetism, thermodynamics and hydraulics are studied (one energy system at a time).

UTC takes a different approach.

CONCEPTS IN PHYSICS

The basic ideas, or "concepts," of physics appear in all energy systems, and these concepts relate to one another in similar ways in all systems. UTC unifies technical physics by presenting first the physics concept and then its application in each energy system.

The first concept studied, for example, is that of force, - the physical quantity that produces motion. The basic characteristics of force are followed by a discussion of how this concept applies to "forcelike quantities" in the following energy "systems":

- In mechanical systems <u>force</u> and <u>torque</u> cause motion of mass.
- In fluidal systems <u>pressure difference</u> causes motion of fluids.
- In electrical systems <u>potential difference</u> causes motion of mass.
- In thermal systems <u>temperature difference</u> causes motion of heat energy.

Problems, demonstrations and hands-on laboratory exercises are used to show the application of the concept in each energy system, and to specific devices or processes common in modern technology.

Thus, UTC provides a student with the basic concepts of physics reinforced by practical application and organized into a consistent whole; UTC is readily applied to future technical problems, whether in other courses or on the job.

COMPONENTS OF UTC

UTC incorporates three types of modules.

CONCEPT MODULES

Thirteen concept modules form the backbone of UTC (each presents a single concept in applied physics and discusses the application of that concept in each energy system):

1-0 Force.
2-0 Work.
3-0 Rate.
4-0 Momentum.
5-0 Resistance.
6-0 Power.
7-0 Potential and Kinetic Energy.
8-0 Force Transformers.
9-0 Energy Convertors.
10-0 Transducers.
11-0 Vibrations and Waves.
12-0 Time Constants.
13-0 Radiation.

APPLICATION MODULES

Each of the 170 application modules discusses the application of a single physics concept in a single energy system, and each module includes a laboratory exercise in which students investigate the application. For example, 5ES "Resistance of Wires" (located under Concept 5-0 "Resistance"), discusses the electrical resistance of wires. In the laboratory, students calculate and measure experimentally the resistance of various wires.

SUPPLEMENTARY MODULES

In UTC, mathematics has been reduced to a minimum: one year of high school algebra is adequate preparation. The following eight supplementary modules are available for students requiring additional preparation or review:

S1 Formula Interpretation.
S2 International System of Units.
S3 Logarithms and Exponents.
S4 Angles and Triangles.
S5 Vectors and Scalars.
S6 Dimensional Analysis.
S7 Reading and Drawing Graphs.
S8 Precision, Accuracy, and Measurement.

STRUCTURE OF A UTC MODULE

Each module in UTC contains seven basic elements:

INTRODUCTION

A brief description of the topics to be discussed, and their importance in technology, introduces each module.

PREREQUISITES

A list of prerequisite UTC modules, and notice of any special knowledge or skills required for successful completion of the module, are given.

OBJECTIVES

Specific tasks that a student should be able to accomplish after completing the module are stated in behavioral terms; objectives also are the basis of testing for UTC.

DISCUSSION

This segment is an explanation of the topic to be studied. It contains the appropriate physics as well as examples of its application. The discussion includes development of equations, example problems, figures and tables of useful data. It addresses each of the objectives (except those pertaining directly to a laboratory experiment).

LABORATORY (called DEMONSTRATIONS in the Concept Modules)

The laboratory section of UTC modules consists of the following three parts:

- "Materials." A list of all equipment and supplies required for the laboratory.
- "Procedure." A step-by-step set of instructions for performing the experiment.
- "Data." An organized format for recording all necessary data and observations.

SELF CHECK

A set of questions and problems based on the module objectives is included. It is intended for use by students to check their own understanding of module content.

REFERENCES

This list of sources directs students to additional information on topics discussed in the module.

TABLE OF CONTENTS

2-0	Work
2M1	Work Done on an Elevator
2M2	Work Done by a Winch
2F1	Work Done by a Water Pump
2F2	Work Done by a Hydraulic Lift
2T1	Heat Energy Required for a Temperature Increase
2T2	Heat Energy Required for Melting
2T3	Heat Energy Required for Boiling
2T4	Fundamentals of Air Conditioning

INTRODUCTION

Years ago, most work accomplished was through physical efforts of men and animals. Today, less than three percent of the energy required by industry is provided by muscular exertion. Modern industries are highly mechanized. Even many machines are controlled by mechanical devices rather than by men. "Work" has become a technical term, and scientists and technicians must define it in a technical way. In this module, work will be defined, and various applications of work in the fields of mechanical, fluidal, thermal and electrical energy will be shown. Energy will be defined also, and units for work and energy will be introduced.

PREREQUISITES

The student should have completed Concept Module 1-0, "Force."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define work and energy in general terms that apply to any energy system, and distinguish work from energy in the following systems:

  Mechanical translational.
  Mechanical rotational.
  Fluidal.
  Electrical.
  Thermal.

- Define the following units of work and energy:

  Foot-pound.
  Newton-meter.
  Joule.
  Calorie.
  British Thermal Unit.

- Define the following terms and explain their usefullness in determining work done:

  Radian (mechanical system).
  Current (electrical system).
  Specific heat (thermal system).
  Heat capacity (thermal system).

- Given two of the following quantities in a mechanical translational system, determine the third:

  Force.
  Displacement.
  Work.

- Given two of the following quantities in a mechanical rotational system, determine the third:

  Torque.
  Angular displacement.
  Work.

- Given two of the following quantities in a fluidal system, determine the third:

  Pressure difference.
  Volume displaced.
  Work.

- Given two of the following quantities in an electrical system, determine the third:

  Voltage.
  Charge transferred.
  Work.

- Given the temperature difference across a uniform thickness of a substance, the dimensions of the substance, and its thermal conductivity, calculate the heat flow rate through the substance.

- Given two of the following quantities in a thermal system, determine the third:

  Temperature change of object.
  Heat capacity of object.
  Work (heat energy transferred).

- Define and give examples of:

  Latent heat.
  Sensible heat.

- State the general equation for work, and explain how it applies to each of the following energy systems:

  Mechanical translational.
  Mechanical rotational.
  Fluidal.
  Electrical.
  Thermal.

WORK AND ENERGY

In Module 1-0, "Force," forcelike quantities were defined as those physical quantities that produce motion in mechanical, fluidal, electrical and thermal systems.

If no net force, net torque, pressure difference, voltage difference or temperature difference is present, the system is in equilibrium and there will be no change in the system.

The forcelike quantities in a system in equilibrium are balanced in such a way that they produce no change. In mechanical systems, this state of balance occurs when the sum of all forces and torques is zero, which means that objects at rest remain at rest and that objects in motion continue the same motion with no change. In fluidal systems, equilibrium occurs when the pressure difference in the fluid is zero, indicating that there is no fluid flow. In electrical systems, no charge moves between two points if the sum of the voltages between them is zero. Thermal equilibrium exists in a closed system only when there is no temperature difference in that system. This condition means that heat energy is not moving in the system. A system in equilibrium experiences no change, although separate forcelike quantities (which add to zero collectively) are present in the system.

If equilibrium does not exist in a system, that system changes in response to the unbalanced forcelike quantities present. Work is done any time that a forcelike quantity produces a change in a system. The amount of work done depends upon both the magnitude of the forcelike quantity that produces the change and the magnitude of the change produced. Work is a description of change in a system, and occurs only when the system is not in equilibrium.

Energy is the ability to do work. Energy is present whenever forcelike quantities are present, even if the system is in equilibrium. When any physical system in equilibrium is changed in such a way that it no longer is in equilibrium, energy is converted to work, and the system changes in some way until a new equilibrium condition is reached. Work and energy are measured in the same units, and the total amount of "work done" always equals the total amount of "energy used." This principle is called "the law of conservation of energy." It means that energy is neither created nor destroyed, but is only changed from one form to another by the process of doing work — or causing change — within a system.

The general formula for determining the amount of work done in any system is given in Equation 1.

$$\text{WORK} = \text{FORCELIKE QUANTITY} \times \text{DISPLACEMENTLIKE QUANTITY} \quad (1)$$

In the remainder of this module, this equation is applied to mechanical, fluidal and electrical systems. The discussion of thermal systems will show that this general equation is not useful in describing heat energy.

MECHANICAL SYSTEMS

MECHANICAL WORK, TRANSLATIONAL

In the mechanical translational system, the general equation for work takes the form of Equation 2.

$$W = F\ell \qquad (2)$$

where

W = mechanical work done by a force.
F = magnitude of component of force acting in the direction of motion.
ℓ = distance through which force acts.

This equation defines only the work done by a force. It does not indicate the final form taken by the energy change produced, but only that a mechanical force has done work to change the form of energy in a system. According to this definition of work, the object must be moved, or no work is done.

In Figure 1, a man has done mechanical work by lifting a weight from the floor. The force exerted by his muscles has moved the weight through a distance. If he had not been able to lift the weight, no work would have been done. The man can tug and strain at the weight; but if he is unable to lift it, he does no work on the weight. When he holds the weight above his head, he is doing no work on the weight, because it is not being moved by a force. How tired he becomes is not involved in the definition of mechanical work. The energy expended by his muscles in holding the weight is converted to heat and to chemical energy, not to mechanical work.

FIG. 1

Example A illustrates the use of Equation 2 in determining work.

EXAMPLE A: WORK DONE LIFTING A WEIGHT.

Given: A man lifts a 200-lb weight 6 ft.

Find: Mechanical work done.

Solution: $W = F\ell$

$= (200\ lb)(6\ ft)$

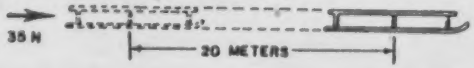
$W = 1200\ ft \cdot lb$

The unit of mechanical work in the English system is the foot-pound — the amount of work done when an unbalanced force of one pound is applied through a distance of one foot. Notice that the unit of work (ft·lb) is the product of the units of force and distance.

In the SI system, the same relationship holds, and the unit of work is the Newton-meter (N·m). This unit is equivalent to one Joule (J) of energy required for accomplishing the work, as shown in Example B.

EXAMPLE B: WORK DONE PUSHING A SLED

Given: A horizontal force of 35N is applied continuously to push a sled through a distance of 20 m.



Find: (a) Work done
(b) Energy used

Solution: (a) $W = F\ell$

$= (35\ N)(20\ m)$

$W = 700\ N \cdot m$

700 N·m of work is done in moving the sled.

(b) Since 1 N·m = 1 J, 700 J of energy was expended in moving the sled.

In determining the work done by a force, only the component of the force in the direction of motion is considered. In Figure 2a, a man pushes a lawnmower. The direction of the force applied to the mower handle and the direction of motion of the mower are not the same. Figure 2b is a vector diagram showing the horizontal (F_x) and vertical (F_y) components of applied force (F). The vertical component of the force does no work, because there is no vertical motion of the mower. Only the horizontal component does work, and its magnitude is used in Equation 2 for determining work. Only the component of the resultant force that lies in the same direction as the resulting motion does work.

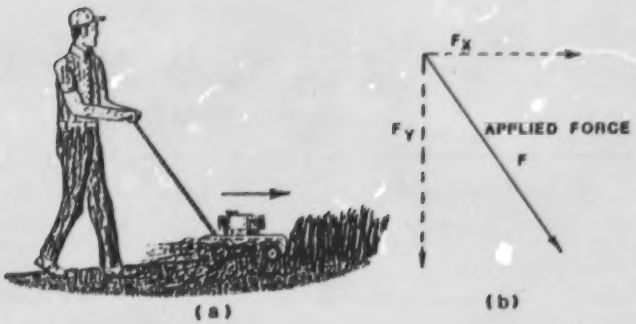


FIG. 2

MECHANICAL WORK, ROTATIONAL

In the mechanical rotational system, the general equation for work takes the form of Equation 3

$$W = \tau\theta \qquad (3)$$

where

W = mechanical work done by a torque.
τ = magnitude of torque producing work.
θ = angle of rotation through which torque is applied.

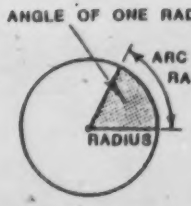


FIG. 3

Angles often are measured in degrees or in number of revolutions; however, a more convenient measure in radians also is commonly used. In Equation 3, the angle must be expressed in radians. An angle of one radian is that angle which, if placed at the center of a circle, would intercept an arc length equal to the radius of the circle. The size of an angle of one radian is shown in Figure 3. This angle of one radian is approximately 57.3°, but an identity derived from the formula for the circumference of a circle is easier to remember. The circumference of a circle encloses an angle of 360°. Since circumference is found by multiplying 2π times radius, and an arc length of one

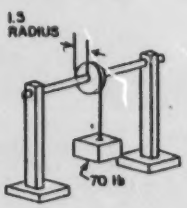
radius corresponds to an angle of one radian: 2π radians = 360°. This relationship and another that results when both sides are divided by two are shown in Table 1.

TABLE 1: CONVERSION FACTORS
2π radians = 360°
π radians = 180°

The radian is not actually a unit in the same sense as a meter or a pound. It is the ratio of the length of an arc to the length of the radius. Lengths are expressed in the same units, which cancel to leave a dimensionless quantity. Thus, when angles expressed in radians are used in calculations, the term "radian" is dropped, as illustrated in Examples C and D.

EXAMPLE C: WORK DONE TO TURN A PULLEY

<u>Given:</u> A force of 70 lb is required to turn a pulley with a radius of 1.5 feet at a constant speed. The pulley turns through 5 revolutions.



<u>Find:</u> Work done on pulley.

<u>Solution:</u> Recall from Concept Module 1-0.

$\tau = Fl$ (Torque = Force x lever arm)

$= (70\ \text{lb})(1.5\ \text{ft})$

$\tau = 105\ \text{ft·lb}$

$\theta = (5\ \text{rev})\left(\frac{2\pi\ \text{rad}}{1\ \text{rev}}\right) = 10\pi\ \text{rad}$

From Equation 3:

$W = \tau\theta$

$= (105\ \text{ft·lb})(10\pi)$ ("rad" is dropped.)

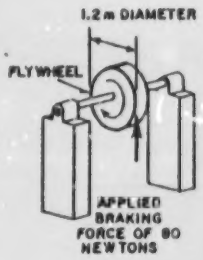
$= (105\ \text{ft·lb})(10)(3.14)$

$W = 4397\ \text{ft·lb}$

4397 ft·lb of work is done by the applied torque.

EXAMPLE D: ENERGY STORED IN A ROTATING FLYWHEEL

Given: A heavy flywheel, 1.2 meters in diameter, rotates 484 degrees before stopping, while a braking force of 80 Newtons is being applied at its outer edge.



Find: Amount of energy consumed in stopping rotation.

Solution: Since diameter = 1.2 meters, radius = 0.6 meters. Energy consumed = work done.

$$W = \tau\theta = F\ell\theta$$

$$= (80\ N)(0.6\ m)(484^\circ)\left(\frac{\pi\ rad}{180^\circ}\right)$$

$$= (48\ N\cdot m)(8.45\ rad)$$

$$W = 405.5\ N\cdot m$$

Energy required to stop flywheel is 405.5 N·m or 405.5 J.

Notice that the units of torque and work are the same - N·m in SI units and ft·lb in English units. This does not indicate that torque and work are equivalent. Care must be taken to identify a quantity expressed in these units as either torque or work. The multiplication of torque (N·m or ft·lb) by an angle of rotation in radians (no units) yields work (N·m or ft·lb). In the SI system, both work and energy usually are expressed in Joules to eliminate the possible misunderstanding.

FLUIDAL SYSTEMS

In a fluidal system, work is accomplished when a pressure is applied to move a volume of fluid. The general formula — Work = Forcelike Quantity x Displacementlike Quantity — takes the form shown by Equation 4 for the fluidal system.

$$W = (\Delta p)V \qquad (4)$$

where

W = work done moving fluid.
Δp = pressure difference through which fluid moves.
V = volume of fluid transferred.

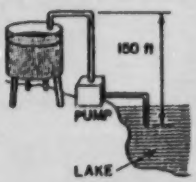
In the fluid system, the forcelike quantity (quantity that causes movement of the fluid) is pressure, and the displacementlike quantity is represented by the volume of fluid moved.

In a system involving liquids, which are incompressible, the volume of a given mass of fluid remains the same; that is, the volume of fluid entering a pipe is equal to the volume leaving the pipe. Volume of fluid is constant, and only fluid pressure changes in the system. Example E illustrates the use of Equation 4 in solving a problem.

EXAMPLE E: WORK DONE TO FILL A WATER TANK

Given: Water tank system of 500 cubic feet. The density of water is 62.4 lb/ft^3.

Find: Amount of energy required to fill it with water from the lake 150 ft below.



Solution: From Concept Module 1-0

Pressure = height x weight density

$p = h\rho_w$

$= (150 \text{ ft})(62.4 \text{ lb/ft}^3)$

$p = 9360 \text{ lb/ft}^2$

The pressure difference Δp between the top of the tank and the surface of the lake is 9360 lb/ft^2.

$W = (\Delta p)V$

$= (9360 \text{ lb/ft}^2)(500 \text{ ft}^3)$

$W = 4{,}680{,}000 \text{ ft·lb}$

The work required to fill the tank is 4.68×10^6 ft·lb.

In cases where the fluid is a compressible gas, the volume change of the gas must also be taken into account when work is calculated.

As previously stated, there must be some movement in the system, or work has not been done. For example, air pressure of forty pounds per square inch in a tire is not work in itself, but work is done in putting air into the tire. The change in tire volume involved in the work is the difference between the volume of air under pressure in the tire and the volume that the same quantity of air would occupy if released to the atmosphere. The pressure involved is the pressure of the air in the tire at any time which increases gradually from one atmosphere (14.7 lbs/in^2) to the final pressure in the tire.

Work done in filling a tire with air is stored in increased thermal energy of the air molecules within the tire as indicated by a rise in temperature and in the stretched tire itself. A mechanic must exercise caution in filling an automobile tire (or tube) with air after repairing it, because this stored energy can be released quickly. If the tire and wheel are not put together correctly, the tire can explode and cause serious injury. Businesses involved in changing and repairing large tires provide a heavy safety frame that holds the tire while it is being filled with air.

ELECTRICAL SYSTEMS

In an electrical system, work and energy are measured in Joules (J). The general formula for work takes the form shown in Equation 5.

$$W = VQ \qquad (5)$$

where

V = potential difference through which charge is moved.
Q = quantity of charge moved.

Potential difference, measured in volts (V), is the forcelike quantity. Charge, measured in coulombs (C), is that substance in electrical circuits that is moved by a potential difference. Thus, charge is the displacementlike quantity.

A net charge of one coulomb represents 6,250,000,000,000,000,000 more electrons at the negative pole than at the positive pole! Since this number is so large, it usually is written with the aid of scientific notation as 6.25×10^{18}. One Joule of work or energy in the electrical system is the amount of energy required to move one coulomb of charge through a potential difference of one volt. Table 2 gives useful conversion factors for electrical energy.

TABLE 2: CONVERSION FACTORS FOR ELECTRICAL SYSTEMS
1 Joule = 1 volt x 1 coulomb
1 coulomb = charge of 6.25×10^{18} electrons

Example F shows the use of Equation 5 in solving a problem.

EXAMPLE F: ENERGY REQUIRED TO CHARGE A BATTERY

Given: A 6-volt automobile battery stores 8000 coulombs of charge.

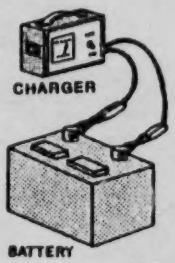
Find: Energy required to charge it.

Solution: $W = VQ$

$(6\ V)(8000\ C)$

$W = 48{,}000\ J$

48,000 J or 48 kJ are required to charge the battery.



In most electrical systems, the measurement of electrical charge is inconvenient. Instead, electrical current is measured. Current is the rate at which charge flows, and is defined by Equation 6.

$$I = \frac{Q}{t} \qquad (6)$$

where

I = current in amperes (A).
Q = charge transferred in coulombs (C).
t = time in seconds (s) required for transfer.

This equation will be examined in more detail in Concept Module 3-0, "Rate." It is presented here only because of its importance in determining work done in an electrical system. Example G shows the use of Equations 5 and 6 in solving for electrical work.

EXAMPLE 6: WORK DONE BY AN ELECTRIC MOTOR	
Given:	A d.c. electric motor, operating on a voltage of 12 V and drawing a current of 4A, runs for 2 minutes.
Find:	Electrical energy consumed.
Solution:	From Equation 6: $Q = It$ $= (4\ A)(120\ s)$ $Q = 480\ C$ The charge transferred is 480 coulombs. From Equation 5: $W = VQ$ $= (12\ V)(480\ C)$ $W = 5760\ J$

THERMAL SYSTEMS

In a thermal system, application of the general work equation — Work equals Forcelike Quantity times Displacementlike Quantity — does not follow the analogy described for the other systems. In thermal systems, the forcelike quantity is identified as a temperature change, and the displacementlike quantity as heat energy. To this point, these analogies provide a systematic unification with the other energy systems. In the application of the work equation, however, the analogy fails. Like all analogies, there may be a situation in which the point of view of the analogy is incapable of clearly describing the situation. Yet in thermal systems, it is quite evident that a temperature difference will cause heat energy to flow and thus, even here, it is useful to identify a forcelike quantity (ΔT) and a displacementlike quantity (ΔH). The analogy is helpful, even though the general work equation (Work = Forcelike Quantity x Displacementlike Quantity) does not hold. Consider, for example, heat flow through a slab of glass (windowpane) or sheet of corkboard as shown in Figure 4. The equation which governs the rate of heat flow through a given thickness or substance, due to a temperature difference ΔT across opposite faces of the substance, is given by Equation 7.

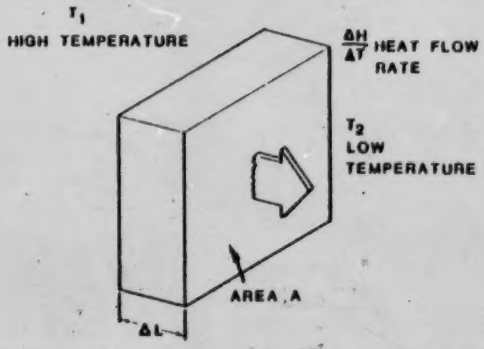


FIG 4

$$Q_H = KA \frac{\Delta T}{\Delta L} \qquad (7)$$

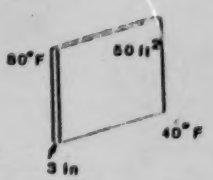
where

ΔT = temperature difference across the substance.
ΔL = uniform thickness of substance.
A = area of substance.
K = thermal conductivity (a constant characteristic of the substance).
Q_H = the heat flow rate (Btu/hr) caused by the temperature difference ΔT across the substance.

It is in thermal systems such as that described by Equation 7 that one sees a compelling similarity between temperature difference ΔT in thermal systems and pressure difference ΔP in fluidal systems or voltage difference ΔV in electrical systems. Each forcelike quantity moves something. In fluidal systems, a mass or volume of fluid is moved. In electrical systems, a quantity of charge is moved. And in thermal systems, a quantity of heat energy is moved. Example H illustrates the use of Equation 7 in a practical problem.

EXAMPLE H: HEAT FLOW THROUGH CORKBOARD

Given: A sheet of corkboard 3 inches thick and 50 ft^2 area. One side of corkboard is at 80°F, the other at 40°F. Thermal conductivity of corkboard is $0.30 \frac{BTU \cdot in}{hr \cdot ft^2 \cdot F^\circ}$.



Find: (a) Forcelike quantity ΔT
(b) Rate of heat energy flow Q_H

Solution: (a) $\Delta T = 80°F - 40°F = 40\ F^\circ$ (forcelike quantity)

(b) $Q_H = KA \frac{\Delta T}{\Delta L}$ (From Equation 7)

$$= \left(\frac{0.30\ BTU \cdot in}{hr \cdot ft^2 \cdot F^\circ}\right)\left(50\ ft^2\right)\left(\frac{40\ F^\circ}{3\ in}\right)$$

$$Q_H = 200 \frac{BTU}{hr}$$

Equation 7 and Example H are concerned with thermal systems where a constant temperature difference is maintained and, as a consequence, heat energy flows from the hot side of the body to the cold side. Here the constant temperature difference ΔT can be viewed as causing heat to flow. In other thermal systems, such as that illustrated by heating a pot of water on a stove, the temperature of the water changes as heat energy flows from the hot stove into the water. In this instance, it is the temperature difference ΔT between the hot stove and cool water that moves heat energy into the water, and as a result, the cool water undergoes a temperature change of its own. The temperature change of the water can be determined from knowledge of the heat energy flowing into the water and properties of the water alone, without knowledge of the temperature difference ΔT between stove and pot.

For example, the quantity of heat energy required to change the temperature of a body (such as the pot of water) is given by Equation 8.

$$H = mc\,\Delta T \qquad (8)$$

where

- H = thermal energy added to the body to cause a temperature change ΔT.
- ΔT = temperature change of the body.
- m = mass of body that undergoes change ΔT.
- c = constant characteristic of the body known as the specific heat of the substance.

In this equation, the quantity mc is the product of the mass and the specific heat of the body that undergoes the temperature change. The product mc is called the "heat capacity" of the object and represents the amount of heat energy required to raise the temperature of that body by one degree (Fahrenheit in English units and Celsius in SI units).

In thermal systems, the quantity of heat energy that flows from higher to lower temperature regions is driven by the temperature difference. In essence, heat energy transferred to a substance actually is the increased motion of the molecules in the substance. Thermal properties of different substances vary widely and depend intimately upon molecular structure of the substances.

Specific heat indicates how many units of heat energy are required to raise a unit mass of some substance a unit temperature difference. Water, for example, has a specific heat of 1 cal/g·C°, or 1 Btu/lb·F°. Since water has a specific heat — that is, an ability to soak up large amounts of heat energy at the expense of only a small increase in temperature — it makes an ideal coolant.

That's why water is used as the coolant in most systems in which considerable thermal energy is generated.

In SI units, quantity of heat is measured in calories (cal) or kilocalories (kcal). One calorie is the amount of heat required to raise one gram of water one degree Celsius. Since the calorie measures small amounts of heat, kilocalories (kcal) often are used to measure larger quantities. Measures of the heat values of foods, incorrectly given as calories in diet books, actually are kilocalories. For instance, bread claimed to have 60 calories per slice actually has 60 kilocalories per slice.

In English units, quantity of heat is measured in British thermal units (Btu). One British thermal unit is the amount of heat required to raise one pound of water one degree Fahrenheit. This unit is used in the United States to measure cooling capacity of air conditioners or heating capacity of stoves. Table 3 lists some useful conversion factors.

TABLE 3: CONVERSION FACTORS
1 Btu = 252 cal
1 kcal = 1000 cal
1 cal = 3.09 ft·lb
1 Btu = 778 ft·lb
1 cal = 4.18 Joules

Specific heats of numerous substances have been determined experimentally and can be found in tables such as Table 4.

TABLE 4: SPECIFIC HEATS OF COMMON SUBSTANCES	
Substance	Specific Heat
Air	0.24
Aluminum	0.22
Brass	0.091
Copper	0.093
Glass	0.21
Iron (steel)	0.115
Stone (average)	0.192
Tin	0.055
Water	1.00
Wood (average)	0.42

Specific heats are stated in Table 4 as the ratio of the specific heat of the given substance to that of water. The value of specific heat of any substance is the same in either SI or English units. Units for specific heat in Table 4 are Btu/lb·F°, kcal/kg·C° or cal/g·C°. Specific heat of water was adopted as a standard because of its large heat capacity and availability.

Use of Equation 8 in thermal systems is illustrated in Examples I and J.

EXAMPLE I: ENERGY REQUIRED TO HEAT WATER

<u>Given</u>: 417 pounds (approximately 50 gallons) of water is heated from 70°F to 130°F (1 ft^3 = 7.48 gal).

<u>Find</u>: Amount of heat energy required. Assume no heat loss in heating water tank or atmosphere.

<u>Solution</u>: Equation 7

$H = mc\Delta T$

$= (417\ lb)(1\ \frac{Btu}{lb \cdot F°})(130°F - 70°F)$

$= (417\ lb)(1\ \frac{Btu}{lb \cdot F°})(60F°)$

$H = 25{,}020\ Btu$

EXAMPLE J: HEAT ENERGY REMOVED TO COOL AN OBJECT

<u>Given</u>: A 25-kg brass ball at 100°C has cooled to 30°C in an insulated container of water. The water temperature increases from 10°C to 30°C.

<u>Find</u>: (a) Amount of heat energy removed from the ball and added to the water.
(b) Mass of water in container.

Assume no heat loss to container or atmosphere.

Solution: (a) $H = mc\Delta T$

$= (25\ kg)(0.091\ \frac{kcal}{kg \cdot C^\circ})(100^\circ C - 30\ C^\circ)$

$H = 159.3$ kcal, or 159,300 cal

(b) $m = \frac{Q}{c\Delta T}$

$= \frac{(159{,}200\ cal)}{(1\ \frac{cal}{g \cdot C^\circ})(20C^\circ)}$

$m = 7965$ g

CHANGE OF STATE

If heat is supplied to matter, two possible changes can occur. The first possible change, described above, is that the temperature of the material will be raised while its state remains fixed. The second possible change is that the temperature will remain fixed, but the state of the substance will change; that is, the substance will change from a solid to a liquid, or from a liquid to a gas. Heat can change the temperature or the state, but not both at the same time.

If the temperature of a material is changing, heat supplied to the material is classified as "sensible heat," since the effect can be sensed by means of a thermometer. If the state of the substance is changing, the heat is termed latent heat. The word "latent" means "hidden." Figure 5 shows a container of ice, to

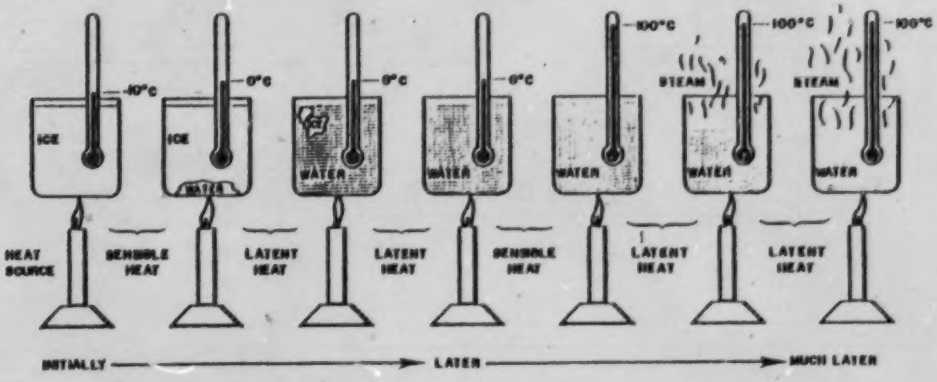


FIG. 5

which heat is applied. The resulting temperatures at various times in the heating process are shown. Latent heat is energy used in changing matter from one state to another. Change of state is a very important principle used in air conditioners, in refrigerators, and in many other cooling and heating systems. Calculations involving latent heat are included in application modules.

SUMMARY

Work is done in any physical system whenever a forcelike quantity causes a change (displacementlike quantity) within the system. Energy is the ability to do work, and is conserved within a closed system. When a system is in equilibrium, it contains energy, but no work is being done, because no displacement is occurring as the result of forcelike quantities within the system. When a system is not in equilibrium, displacement of some kind occurs as the result of forcelike quantities; and energy is converted to work within the system. Work and energy are equivalent and are measured in the same units. Table 5 shows the general work equation and the form it takes in mechanical, fluidal and electrical systems. The equation for heat energy required for a temperature increase also is included, although it is not derived from the general work equation.

TABLE 5: WORK AS A UNIFYING CONCEPT

ENERGY SYSTEM	WORK = FORCELIKE QUANTITY x DISPLACEMENTLIKE QUANTITY
MECHANICAL	
Translational	Work = Force x Displacement (in direction of force)
Rotational	Work = Torque x Angular displacement
FLUIDAL	Work = Pressure Difference x Volume change
ELECTRICAL	Work = Potential Difference x Charge transferred
THERMAL	Heat Energy = Temperature change x Heat capacity

MECHANICAL SYSTEM. LINEAR WORK

MATERIALS

Mass (can be cardboard box with something heavy in it) approximately 10 kg.
Balance.
Meter stick.

PROCEDURE

In this experiment, the work done in lifting an unknown mass and placing it on a table is calculated.

1. Lift unknown mass from floor onto scale (Figure 6).
2. Determine mass of object with a balance scale.
3. Measure distance object was lifted to place it on table.
4. Fill in Data Table 1; calculate work done in lifting mass to table.

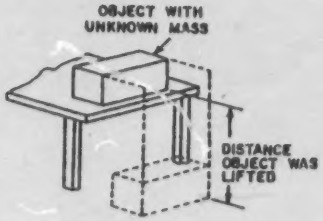


FIG. 6

DATA TABLE 1		
Mass of Object Lifted	Distance Object Was Lifted	Work Done Lifting Mass
		N-m
		J
		ft-lb

MECHANICAL SYSTEM, ROTATIONAL WORK

MATERIALS

Gyroscope (lab model or toy).
Pulley and bracket for table mount.
Micrometer.
200 g mass.
String.

PROCEDURE

Determine work done in spinning gyroscope illustrated in Figure 7.

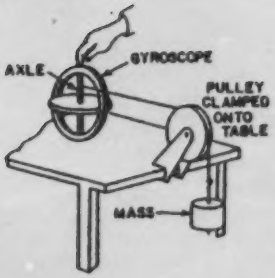


FIG.7

1. With a micrometer, measure diameter of gyroscope axle. Calculate radius of axle.

2. Count number of revolutions used in winding up string. Do not tie string to axle.

3. Hold gyroscope carefully, and place string across a pulley mounted on table. Suspend a mass of approximately 200 g on string so that when string is released, weight will fall toward floor, in such a manner that a constant force is applied on string. String should be completely unwound before weight strikes floor.

4. Fill in Data Table 2, calculate torque on axle and work done in spinning gryoscope wheel.

DATA TABLE 2							
Axle		Number of		Mass on String	Force on String (N)	Torque	Work
Diameter	Radius	Revolutions	Radians				
_____ mm _____ in	_____ m			_____ g	_____ N	_____ N-m	_____ N-m
Recall that 2 rad = 1 revolution. Recall that 1 kg weighs 9.8 N.							

FLUID SYSTEM, WORK

MATERIALS

Rubber hose.
2 hose clamps.
Pressure gage (0-100 psi).
Gallon jug (such as a milk jug).
Beaker, graduated in liters.

PROCEDURE

In this experiment, work done in filling a gallon container from a water faucet will be determined.

1. Insert one end of a rubber hose on a pressure gage, and clamp securely. Clamp other end of hose securely to water faucet. Turn on water fully, and measure water pressure at faucet.

2. Fill jug with water from faucet.

3. Measure water by pouring it into a beaker graduated in liters.

4. Fill in Data Table 3; calculate work done in filling jug.

DATA TABLE 3		
Water Pressure at Faucet	Volume of Jug	Work Done in Filling Jug
_____ psi	_____ gal	_____ ft·lb
_____ N/m^2	_____ cm^3	_____ N·m
	_____ m^3	_____ J
Recall 1 lb/in = 6895 N/m^2 1 liter = 1000 cm^3		

ELECTRICAL AND THERMAL SYSTEMS WORK

MATERIALS

Balance.
Small piece of thin, copper wire, approximately 1 1/2 meters long (20 gage or equivalent).
6- or 12-volt storage battery.
Styrofoam plastic cup and block of styrofoam to use as a lid.
Two alligator clip leads for power source.
Voltmeter.
Thermometer (1°C graduations).

PROCEDURE

This experiment will combine electrical and thermal systems in one experiment. Electric potential will be supplied to a small, thin copper wire immersed in a styrofoam cup filled with water. As charge moves through the wire, heat is generated.

1. Measure emf or battery or power source.

2. Measure mass of water in styrofoam cup on balance scale.

3. Record temperature of water in cup before power source is connected.

4. Form copper wire into a coil, being careful not to touch bare wires. Connect clip leads, and immerse coil in water (Figure 8).

5. Connect power source. Keep voltage across wire small enough that no boiling occurs. After temperature has increased about 10 degrees, disconnect all leads, and record temperature.

6. Fill in Data Table 4, calculate heat energy supplied to water (calories) and electrical energy necessary to supply that heat.

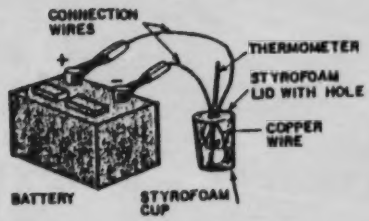


FIG. 8

DATA TABLE 4		
Mass of water in cup	_____	g
Beginning temperature	_____	°C
Final temperature	_____	°C
ΔT	_____	°C
Heat energy supplied (Equation 5)	_____	cal
Electrical energy used to supply heat*	_____	J
emf (from voltmeter)	_____	V
Charge transferred (Equation 6)	_____	C
Electrons transferred	_____	electrons

*1 cal = 4.18 J.
**1 C = 6.25×10^{18} electrons.

The student should realize that more electrical energy actually was supplied than needed to heat the water alone. Where is this additional energy consumed?

SELF CHECK

1. Define work and energy, and state the similarities and differences of the two concepts.

2. Define the following units of work and energy, and state the energy systems in which each is used.

   a. Foot-pound.
   b. Newton-meter.
   c. Joule.
   d. Calorie.
   e. British thermal unit.

3. Define the following terms:

   a. Radian.
   b. Current
   c. Specific heat.
   d. Heat capacity.

4. A force of 70N is applied to slide a box a distance of 500 m. How much work is done?

5. 45 ft·lb of work is required to lift an object a distance of 15 ft. How much does the object weigh?

6. A torque of 280 ft·lb does 12 ft·lb of work. What is the angle of rotation in radians and degrees?

7. Explain the two meanings of the English unit ft·lb.

8. How much work is done in removing a nut from a bolt if an average torque of 70 N·m must be supplied for 4 1/2 revolutions? How many ft·lb of work are required?

9. A pump consumes 13,000 J of energy when moving 18 m^3 of water under constant pressure. What pressure (N/m^2 and lb/ft^2) did the pump supply to the water?

10. An air conditioner is capable of providing an air pressure of 1/4 psi. How much energy is required to fill a room 20 ft x 30 ft x 8 ft with cool air?

11. How many calories of heat are required to raise the temperature of 500 g of copper from 29°C to 95°C? (See Table 3.)

12. A household refrigerator may be considered as a "box" of corkboard 2.5 inches thick and 45 square feet of area. Under normal operating conditions (closed door), the interior is maintained at 40°F while the exterior (room temperature) may be around 70°F. If the refrigerator motor runs one-fourth of the time to maintain this temperature difference, at what

rate in BTU/hr must heat energy be withdrawn from the inside of the refrigerator while the motor is running?

13. If a 12-V (d.c.) electric refrigerator consumes 1800 J of energy over a certain period of time to keep food cold, how much charge (coulombs) has been moved?

14. A beaker of water is heated from 25°C to 75°C by the addition of 90 Btu of heat energy. Determine the mass of water heated.

15. Define and give examples of sensible heat and latent heat.

16. State the general equation for work, and explain how it applies in each of the following energy systems:

    a. Mechanical rotational.
    b. Mechanical translational.
    c. Fluidal.
    d. Electrical.
    e. Thermal.

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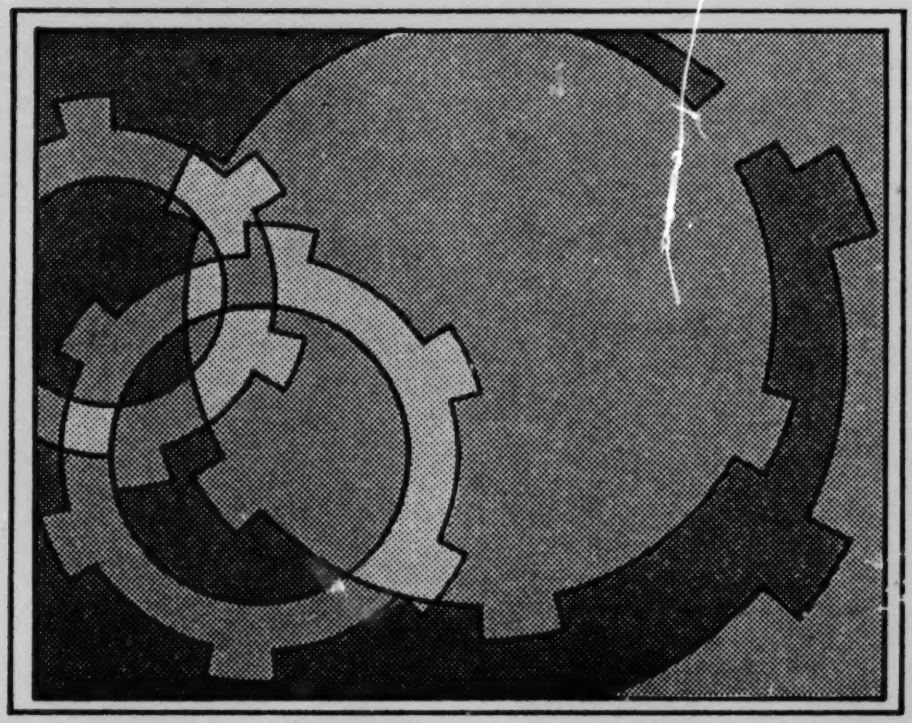
UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 2 M 1

WORK DONE ON AN ELEVATOR



MECHNICAL APPLICATION OF WORK

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Since their invention, elevators and escalators have been used to lift loads against the force of gravity. Different types of machinery can provide the energy to do the lifting work. This work may be delivered as fluid energy in a hydraulic automobile lift and as rotational mechanical energy in a motor and winch attached to an elevator. In this module, the mechanical work required to lift objects against the force of gravity is defined and the inclined plane and its advantages in lifting discussed. In the laboratory, the student will determine the work required to lift objects vertically and on an incline.

PREREQUISITES

Student should have completed Concept Module 2-0, "Work."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define work in a mechanical system in terms of an equation that relates force and displacement.
- Calculate the work done on the body, given a force vector applied to a body and a displacement distance.
- Calculate the work done on an elevator, given an elevator weight, load, and vertical distance of travel.
- Given the appropriate equipment, determine (1) the work required to move a weight vertically and (2) the work necessary to move a weight up an inclined plane, neglecting friction.

WORK DONE ON AN ELEVATOR

Busy, multi-story business buildings usually contain one or more elevators. The elevators are used to transport people from one floor to another, saving them the effort of climbing long flights of stairs. The elevators travel in a vertical plane and are propelled by cables attached to winches (Figure 1). These winches usually are powered by electric motors housed at the top of the elevator shafts. The electric motor turning the winches causes the cables to exert a work-producing force on the elevators. Elevators are designed to stop and start smoothly as they travel the vertical shaft. If the passenger desired to travel several floors, the elevator accelerates smoothly as it lifts and maintains a constant speed until it decelerates smoothly to a stop at the desired floor. The safe maximum load is posted inside most elevators to prevent overloading. The work required to cause an elevator to be lifted through the vertical distance originates in the electric motor and winch-cable combination. The amount of work provided must be not only the work required to lift the elevator, but also the work required to overcome friction in all moving parts of the elevator.

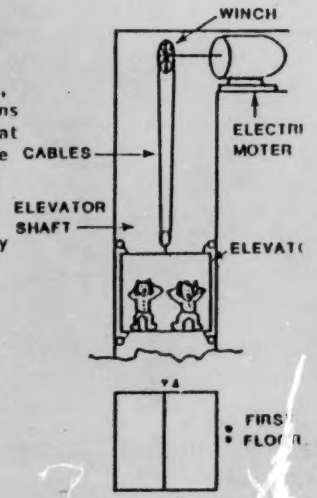


FIG. 1

WORK IN A MECHANICAL SYSTEM

In Concept Module 2-0, "Work," mechanical work was defined by Equation 1 and is repeated in this module as Equation 1.

$$W = F\ell \qquad (1)$$

where

W = mechanical work done by a force.
F = magnitude of component of force acting in the direction of motion.
ℓ = distance through which force acts.

Both force and displacement are vector quantities, and their vector direction is of fundamental importance. The force vector in Equation 1 must be in a direction parallel to that of the displacement vector. This relationship is illustrated in Figure 2.

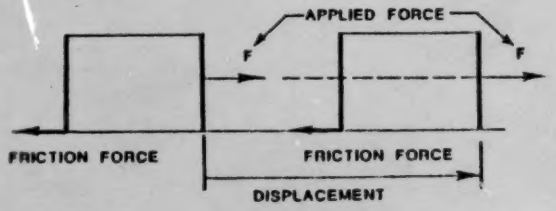


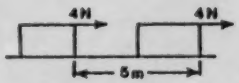
FIG. 2

Note also that in Figure 2 the object being moved has a friction force whose vector sense is opposite to the sense of the displacement vector. Its line of action still is parallel to the displacement vector and, therefore, does work on the object. Often, one must consider the work done by each force on an object separately. This concept will be applied to a discussion of the elevator later in this module.

Although work is the product of two vector quantities, it is a scalar quantity without direction, like other scalar quantities of volume and area. Work often is graphically depicted as the area under a force-displacement curve. For applications in which the force may vary over the displacement, the graphical method of determining work on an object is very useful. Example A illustrates this principle.

EXAMPLE A: WORK AS AREA UNDER A CURVE

Given: An object having a single constant force of 4 Newtons applied to it moves through a distance of 5 meters in the direction of the force.



Find:
(a) The mechanical work done.
(b) How the mechanical work equals the area underneath a force-distance curve.

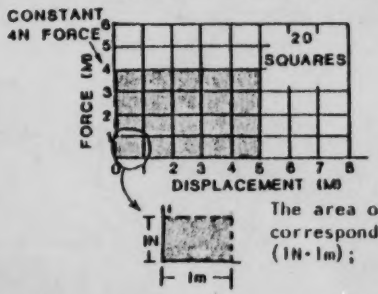
Solution: (a) $W = F\ell$

$= (4N)(5m)$

$= 20\ N \cdot m$

$W = 20\ J$

(b) Draw a force-displacement graph:



The area of each square of graph corresponds to 1 Joule of work (1N·1m);

therefore, the mechanical work done by the force is

$$(20 \text{ squares})\left(\frac{1 \text{ Joule}}{\text{square}}\right) = 20 \text{ J}$$

WORK AGAINST GRAVITY ON AN ELEVATOR

Figure 3 is a diagram of an elevator's motion from the first to the tenth floor. In the following discussion, frictional energy losses will be neglected. As the elevator leaves the first floor, the applied force must be greater than the weight of the elevator for the acceleration-to-speed to occur. Therefore, the work done

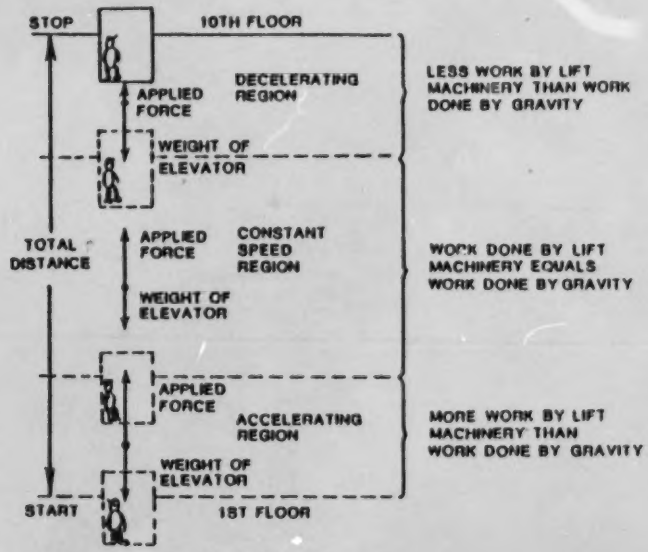


FIG 3

by the lift machinery supplying the applied force through the cables must exceed the work done by the gravitational force through the acceleration region. The difference goes into the increasing kinetic energy of the elevator. As the elevator reaches its maximum allowable speed, the applied force in the cables equals the weight of the elevator. When this happens, the elevator moves at a constant speed; and the work done by the lift machinery is equal to the work done by gravity. In this constant-speed region of motion, the net force on the elevator is zero; and the net work on the elevator is zero, although it is moving at constant speed.

This may seem strange, yet Newton's first law of motion states, "In the absence of a net force acting on it, ... a body in motion will remain in motion at constant velocity."

As the elevator approaches the tenth floor, it begins to decelerate. Here, less force is applied to the elevator cables, and less work is done by the lift machinery than the work done by gravity.

While stopping at the tenth floor, the lift machinery must reapply a force through the cables equal to the weight of the elevator. Since the elevator is not moving while at the tenth floor, no work is done on it either by gravity or by the cables.

Calculating the total work done on the elevator by the lift, machinery is not as difficult as it seems. To understand this, observe Figure 4, which shows the force-displacement graph of the elevator's motion. Notice that the "hump" area in the acceleration region of the graph could be chopped off smoothly, flipped upside down, and fitted into the hole of the graph in the deceleration region. The resulting graph is shown in Figure 5.

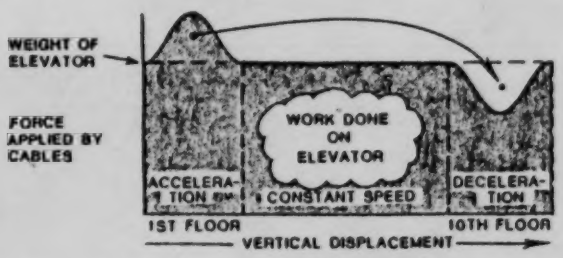


FIG. 4

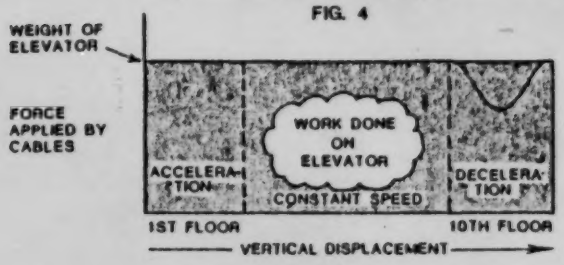


FIG. 5

The graph shows that the work done on an elevator by the lift machinery can be determined because the force applied to the elevator equals the weight of the elevator throughout the vertical displacement. Therefore, the work done on an elevator can be determined by Equation 2.

$$W = W_T h \qquad (2)$$

where

W = work done on an elevator.
W_T = weight of elevator.
h = vertical displacement of elevator.

Actually, this concept can be used to determine the work done against gravity while lifting any body through a vertical displacement. Equation 3 applies for any body being lifted through a vertical displacement.

$$W_g = W_T h \qquad (3)$$

where

W_g = work done against gravity.
W_T = weight of body being lifted.
h = vertical displacement.

Example B illustrates the use of Equation 3 in solving a problem.

EXAMPLE B: WORK DONE ON AN ELEVATOR

Given: A 10,000-Newton elevator plus a 4000-Newton load is lifted through a vertical displacement of 5 floors (7 meters between floors).

Find: The work done by the lifting machinery on the elevator.

Solution: (1) The total weight of the elevator must include dry weight plus load

Total Weight = 10,000 N + 4000 N

Total Weight = 14,000 N

(2) The total vertical displacement

$$\text{Vertical displacement} = (5 \text{ floors})\left(\frac{7 \text{ meters}}{\text{floor}}\right)$$

Vertical displacement = 35 meters

(3) Work done on the Elevator = (Weight of Elevator) (vertical displacement)

= (14,000 N)(35 m)

Work done on the Elevator = 490,000 J

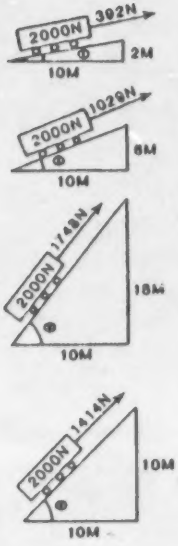


FIG. 6

WORK DONE AGAINST GRAVITY BY USING AN INCLINED PLANE

An inclined plane is a simple machine that allows less force than its weight to be exerted on an object as it travels through a longer distance than the actual vertical displacement. Figure 6 shows an object being moved through a vertical distance by traveling along inclined planes at different angles of incline. The object being moved (Figure 6) has a weight of 2000 N and is pulled on rollers to reduce friction to a minimum. The forces shown would be the forces required to pull the object up the plane at a constant velocity. The effect of friction is not considered.

In Figure 7, an object being rolled up an inclined plane is compared to the same object being lifted through a vertical height. The work done in lifting the object is expressed by Equation 4.

$$W_L = W_T h \qquad (4)$$

where

W_L = work done in lifting.
W_T = weight.
h = vertical height.

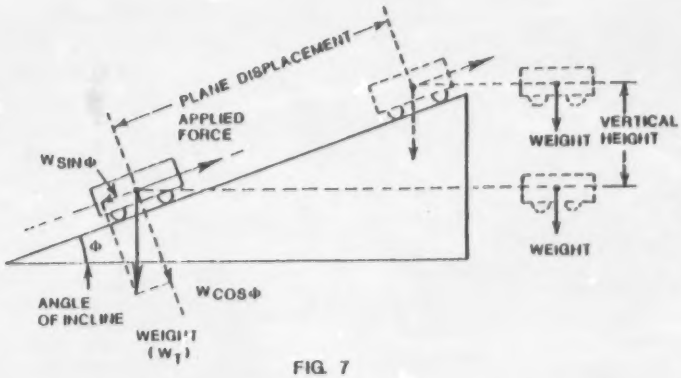


FIG. 7

In order to determine the work exerted on the object along the plane, the weight vector is resolved into components. In Figure 7, one component, W cos θ, perpendicular to the plane does no work. The other component, W sin θ, must equal the applied force, F, as the object is moved in a displacement along the plane. Therefore, the work done along the plane is given by Equation 5.

$$W_p = F\ell \tag{5}$$

where

W_p = work along the plane.
F = applied force.
ℓ = plane displacement.

or,

$$W_p = W_T \sin\theta\ \ell \tag{6}$$

By the definition of sin θ, this work is —

$$W_p = W_T\left(\frac{h}{\ell}\right)\ell.$$

According to Equation 4, however, the following is true:

$$W_p = W_L \tag{7}$$

The inclined-plane principle is applied in lifting people in busy department stores by an escalator. The unit powering the escalator can apply less force along the plane of the escalator, and more people can be moved than with the elevator.

SUMMARY

Work done by an elevator's lift machinery to supply force through the cables must exceed the work done by gravitational force through the acceleration region. The work done on the elevator by the lift machinery can be determined because the force applied to the elevator equals its weight throughout the vertical displacement.

WORK DONE IN LIFTING A MASS THROUGH A DISTANCE

MATERIALS

Hanging spring scale (calibrated in Newtons).
1000-gm mass with hook.
Meter stick.

PROCEDURE

In this experiment, the student calculates the work done in lifting a mass through a distance, notes the effect on the applied force while starting and stopping the mass, and compares these effects to the applied force on the mass, if the mass remains motionless.

1. Hang a 1000-gm mass on the spring scale. Record in Data Table the force indicated on scale. Lower mass to floor.

2. Using a meter stick as a guide, raise mass at an extremely slow, constant rate (Figure 8). Record distance traveled in meters.

3. Calculate work done lifting mass, and record in Data Table 1.

4. Lower mass to floor, while carefully observing the scale. Raise mass through one-meter distance at a rapid rate, stopping mass at end of meter distance.

5. At the beginning of the lifting motion, is the scale reading more, or less, than the reading when the scales are motionless?

6. At the top near the end of the lifting motion, is the scale reading more or less than the reading when the scales are motionless?

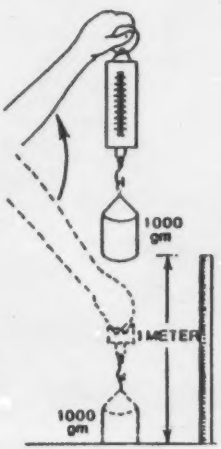


FIG. 8

WORK NECESSARY TO MOVE A WEIGHT UP AN INCLINED PLANE

MATERIALS

Inclined plane with adjustable pulley.
Meter stick.
Hall's car (small metal car with cavity for loading masses; car must have low-friction wheels).
Metric mass set and hanger.
Mass weights of 100, 300, and 500 gram.
String (stout).
Protractor.

PROCEDURE

1. Using a beam balance, obtain the mass of the Hall's car in kilograms, and record it in Data Table 2.

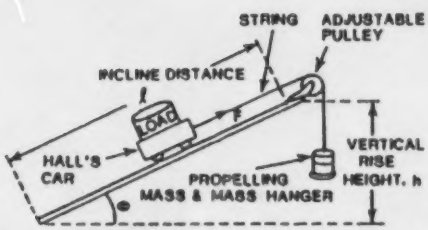


FIG. 9

2. Arrange Hall's car on inclined plane as in Figure 9. Be sure that the adjustable pulley is positioned in such a manner that string attached to Hall's car is parallel to plane.

3. Measure angle of incline θ with a protractor, and record it in Data Table 2.

4. Place a 500-g load mass in Hall's car, and add enough mass to mass hanger so that with a gentle push to overcome friction, the car will move up the plane at a relatively constant speed. If car stops or moves erratically, add slightly more mass to propelling mass hanger. If car accelerates, decrease mass on mass hanger. The purpose of this propelling mass is to provide a constant applied force F to Hall's car throughout its travel up plane. The applied force is provided by gravity, producing constant gravitational force on propelling mass. This force is transmitted to the car by the string, and acts parallel to the incline.

5. Measure an inclined distance ℓ along the plane and record in Data Table 2. Measure vertical rise height h, and record in Data Table 2.

6. Calculate work done on car along plane, and record in Data Table 3.

7. Calculate work done to lift Hall's car plus load through the vertical rise height. Record result in Data Table 3.

8. Find difference in work done on car along plane and work required to lift car through vertical rise height. Record this result in Data Table 3. Explain this difference.

9. Repeat Steps 1 through 8 twice more, changing the loaded mass by 200-gram increments. Record all data in tables as previously instructed.

DATA TABLE 1		
Scale Reading (Force Applied)	= _____	Newtons
Distance Traveled	= _____	meter
Work Done Lifting Mass	= _____	Joule

DATA TABLE 2				
Mass of Car + Load (kgm)	Distance (ℓ) Along Plane (m)	Angle of Incline (degrees)	Vertical Rise (h) (m)	Weight of Car* plus load (Newtons)

$$\text{*Weight of Car in Newtons} = \left[\text{Mass of Car plus load in kgm}\right] \times 9.8 \frac{m}{s^2}$$

DATA TABLE 3		
Work Done on Car Up The Plane (A) (Joules)	Work to Lift Car Through Vertical Rise (B) (Joules)	Difference in Work (A - B) (Joules)

SELF CHECK

1. Define work in a mechanical system in terms of an equation that relates force applied to an object and the displacement through which an object moves.

2. A force of 35 Newtons acts on a body while moving the body through a displacement distance of 15 meters. Calculate the work done on the body by the force.

3. An elevator car weighs 3000 lb. Twelve people, averaging 150 lb each, step on the elevator. The elevator travels 20 floors (assume 25 ft between floors). Calculate the mechanical work required on the elevator car and load in ft·lb. Convert your answer to joules.

4. An inclined plane is used to move an 800-lb piano to the tailgate of a moving van, 4 ft from the street. The plane is 20 ft in length.

   a. How much force is required to move the piano up the plane at a constant speed?
   b. How much work is necessary to move the piano up the plane?
   c. How much work is required for 4 men to lift the piano to the tailgate?

5. In problem 4, how much work would be done if the 4 men held the 800-lb piano 2 ft off the ground for 1 minute?

6. In problem 4, how much work is done by the force of the plane on the piano?

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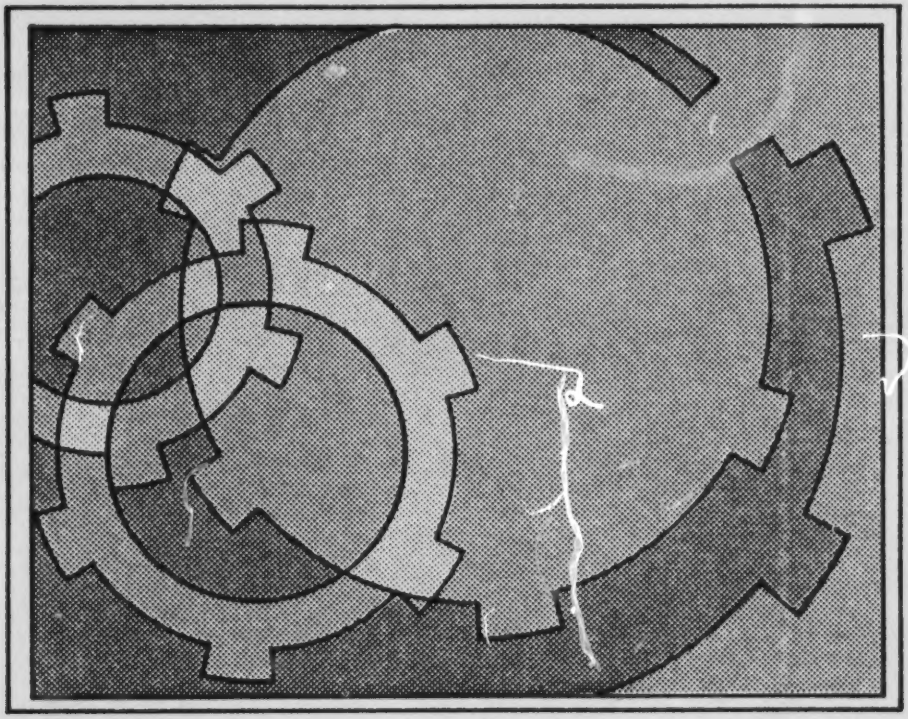
UNIFIED TECHNICAL CONCEPTS

MODULE 2 M 2

WORK DONE BY A WINCH



MECHANICAL APPLICATION OF WORK

Technical Education Research Center-Southwest TERC-SW

INTRODUCTION

The winch is a simple machine which has been used to expand the capacity of man to move heavy objects in the world today. The principle of the winch is applied to many areas of technology and of everyday life, such as the movement of people in elevators and escalators, lifting heavy machinery in industry, and the operation of bicycles and automobile and truck accessories.

This module presents an application of the concept of work in rotational systems, and describes in particular the rotational work into and out of a winch. Other topics discussed include the efficiency of winches, the use of geared winches and the effects of torque variations upon them. In the laboratory, the student will determine the work and efficiency of a winch.

PREREQUISITES

The student should have completed Concept Module 2-0, "Work."

OBJECTIVES

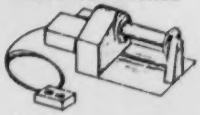
Upon completion of this module, the student should be able to:

- Describe the main design features of a winch and list at least two applications.
- Given a force, a moment arm, and an angle of travel, calculate the rotational work done on a winch and by a winch.
- Calculate the efficiency of a winch, given the output work and the input work.
- Describe the effects of varying the direction of the input force on a winch from directions other than a tangent.
- Given the appropriate equipment, determine the work and efficiency of a winch.

DISCUSSION

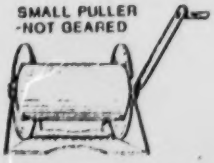
A machine is a force-multiplying device. Its purpose is not to convert one form of energy to another, but merely to exert an output force on an object which is different from (usually larger than) the input force which is applied on the machine. One such machine is the winch. The winch plays an important role in our everyday life.

"PULL POWER" ELECTRIC WINCHES



The winch is characterized by a drum, or axle, about which a rope or cable is wrapped securely. Attached to the drum is a hand crank or a motor by which a force is applied. Figure 1 illustrates several types of winches. A simple hand winch is frequently used by fishermen to pull boats from the water onto boat trailers. The fisherman may also use an electric-powered winch to raise and lower his boat anchor. Even his fishing reel is a simple, hand-powered winch. Some winches magnify the input force through the use of gears. Gears may magnify the input force in such a manner that a 30 lb effort by a man on the handle of a winch pulls a load of 3500 lbs. Winches are used widely in industry for many types of lifting jobs employing floor cranes, portable hoists, power eleveators and escalators.

SMALL PULLER -NOT GEARED



HOIST WINCH

WORK IN A ROTATIONAL SYSTEM

Mechanical work done on a rotating body is defined by Equation 1.

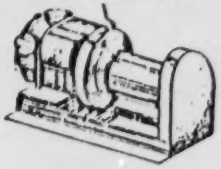
$$W_{ro} = \tau\theta \qquad (1)$$

where

W_{ro} = mechanical work in rotational system.
τ = torque.
θ = angle of rotation.

Mechanical work is measured in units of ft·lbs or Joules (Newton x meter). Figure 2 shows a comparison of mechanical work done in a linear system and mechanical work in rotation system.

POWERED WINCH



GEARED WINCH

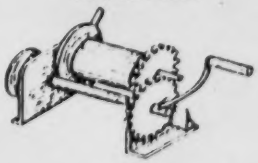
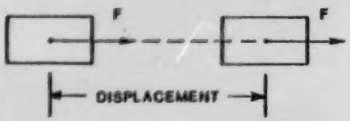


FIG. 1

WORK (LINEAR)	WORK (ROTATIONAL)
	
WORK = FORCE x DISPLACEMENT	Angular WORK = TORQUE x DISPLACEMENT
UNITS FOR WORK:	UNITS FOR WORK:
NEWTON (N) x METER (m)	NEWTON x METER x RADIANS
OR	OR
JOULE (J)	JOULE (J)

Note that radian is a dimensionless quantity and does not affect the final units.

FIG. 2

In Figure 2, force in the linear system is in the same direction as the displacement vector throughout the motion of the body. In the rotational system, force F always remains perpendicular to the radius as the wheel moves through the angular displacement, θ.

OPERATING PRINCIPLES OF A SIMPLE HAND WINCH

In Figure 3, a simple hand-operated winch is shown with a force being applied to the handle. This force is normally much smaller than the weight being lifted. The handle moves through the same angular displacement, θ, as does the winch drum. The torque produced by the hand on the handle about the axis of the drum is called input torque and is given by Equation 2:

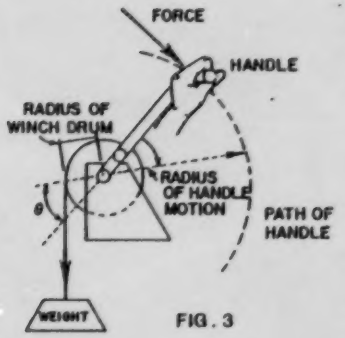


FIG. 3

$$\tau_{in} = F_{in}\, r_{in} \qquad (2)$$

where

τ_{in} = input torque.
F_{in} = input force (of hand).
r_{in} = radius of handle.

The longer the radius of the handle, the smaller the force required to produce a given

amount of torque about the drum axis. Equation 2 is valid only if the force exerted by the hand is applied perpendicularly to the radius of the handle. The input work on the winch is given by Equation 3.

$$W_{in} = F_{in} r_{in} \theta_{in} \quad (3)$$

where

W_{in} = work input.

Example A shows how Equation 1 is used in solving a problem.

EXAMPLE A: WORK INPUT TO A WINCH

Given: A hand winch whose handle radius is 30 cm long has a force of 150 N of force applied perpendicularly, through an angle of travel of 5 complete revolutions.

Find: Input work to the winch.

Solution: The angle of travel in radians is

$$\theta = t \text{ revolutions} \times \frac{2\pi \text{ radians}}{\text{revolution}}$$

$$= 10\pi \text{ radians}$$

$$\theta = 31.4 \text{ radians}$$

ANGLE OF TRAVEL= 5 REVOLUTIONS

Calculating the WORK INPUT

$$W_{in} = F \times r \times \theta$$

$$W = (150 \text{ N}) \times (0.3 \text{ m}) \times (31.4)$$

$$W_{in} = 1413 \text{ J}$$

The load, or weight, acting upon the cable of the winch shown in Figure 3 is the output force, which produces an output torque acting around the radius of the drum cable, r. As the load or weight is lifted, the cable always wraps around the drum in a manner that this load force is always perpendicular to the radius of the drum. The output torque produced by the winch is given in Equation 4.

$$\tau_{out} = F_{out} r_{out} \quad (4)$$

where

τ_{out} = output torque.

F_{out} = output force load.

r_{out} = radius of winch drum with cable.

The work done by a winch is given by Equation 5.

$$W_{out} = F_{out}\, r_{out}\, \theta_{out} \qquad (5)$$

where

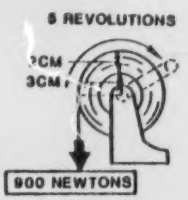
W_{out} = work output.
θ_{out} = output angular displacement.

Example B shows the use of Equation 5 in calculating the work done by a winch.

EXAMPLE B: WORK OUTPUT BY A WINCH

Given: A hand winch whose drum radius is 3 cm. A thickness of wrapped cable of 2 cm is attached to the drum. A load force of 900 N is applied to the winch cable. The winch drum turns 5 complete revolutions.

Find: The work output by the winch.



Solution:

1) The angle of travel, θ, as in Example A is 31.4 radians.

2) The total winch drum radius must equal the cable-wrap thickness plus the drum radius, or 5 cm.

3) Calculating the WORK OUTPUT,
$W_{out} = F\, r\, \theta$
$W_{out} = (900\ N) \times (0.05\ m) \times 31.4$
$W_{out} = 1413\ J$

Examples A and B refer to the same hand winch. Input work equals the output work; this situation occurs whenever friction is negligible. Actually, the input work must be slightly greater to overcome the frictional energy losses in the winch. The winch is a very simple machine. Friction encountered in the winch can be very low; thus, the efficiency of the winch can be quite high.

The efficiency of machinery, in general, is defined as the ratio of the OUTPUT WORK to the INPUT WORK, as shown in Equation 6.

$$\eta = \frac{W_{out}}{W_{in}} \ (100) \qquad (6)$$

where

η = % efficiency.
W_{in} = work input.
W_{out} = work output.

Efficiency usually is expressed as a percent. Therefore, the decimal fraction which results from a calculation with Equation 6 is mulitplied by 100 to give the percent efficiency. Example C illustrates the use of Equation 6 in the calculation of the efficiency of a winch.

EXAMPLE C: EFFICIENCY OF A WINCH

Given: A winch has 5600 J of work done on it (input work). The output work done by the winch is 5200 J (400 J of work done to overcome friction).

Find: Efficiency of the winch in percent.

Solution:

$$\eta = \frac{W_{out}}{W_{in}} \quad (100)$$

$$= \frac{5200\ J}{5600\ m} \times 100$$

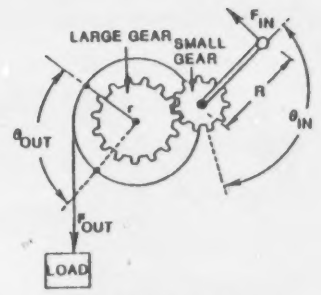
$$= 0.93 \times 100$$

$$\eta = 93\%$$

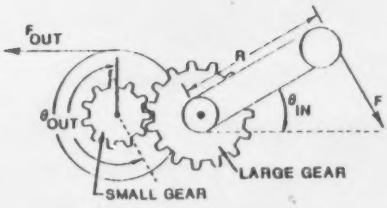
Normally winches are highly efficient. The efficiency of the ideal winch illustrated in Examples A and B is 100%, representing the maximum limit of efficiency for any machine. A 100% efficient machine would have no friction losses.

WINCHES WITH GEARS

Often modern-day winches contain gears between the winch drum and the crank mechanism. The purpose of the gears is to require less applied force to the cranking mechanism at the expense of a greater amount of angular travel. With the simple hand crank, the angular displacement of the cranking mechanism is the same as the angular displacement of the winch drum. With a winch having gears, the angular displacement of the winch drum is much different from the angular displacement of the crank mechanism, as shown in Figure 4. Figure 4 illustrates two types of gearing for different winch applications. The geared lift winch in Figure 4a has a small gear on the crank mechanism, while the larger gear is on the winch drum, which causes the angular displacement of the winch drum, θ_{out}, to be much smaller than angular displacement of the crank mechanism θ_{in}. The speed winch (Figure 4b) has a different purpose. Its



(a) GEARED LIFT WINCH



(b) A SPEED WINCH

FIG. 4

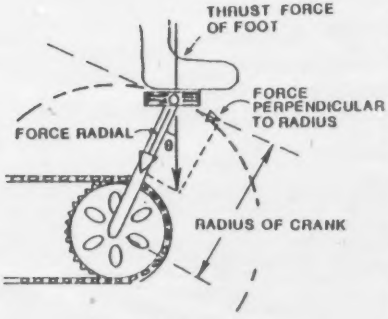


FIG. 5

major purpose is to take up line or cable at a fast rate; therefore, the crank handle is attached to the larger gear, and the small gear is attached to the winch drum. This arrangement causes the angular displacement of the winch drum to be much larger than the angular displacement of the crank mechanism. No matter what the angular displacement relationship caused by gears is, the WORK INPUT to the winch is still only slightly greater than the WORK OUTPUT; and the winch efficiency is still high. The WORK INPUT and the WORK OUTPUT are still calculated from Equations 3 and 5, respectively. The use of gears in a winch causes additional friction that must be overcome by input force.

VARIATION OF TORQUE ON A WINCH

As previously stated, the input force to a winch should be applied perpendicularly to the radius of the crank mechanism. In practice, this is not always the case. Frequently, force is applied in a different direction, causing torque on the crank to be less than expected. How this relationship happens is illustrated in Figure 5, in which a bicycle crank is shown.

The thrust force of the foot is not always directed perpendicularly to the radius of the crank. If the thrust force is resolved into two components - one along the radius of the crank, the other in a direction perpendicular to the crank radius - a physical significance can be given to these components. The radial portion (component) of the thrust force causes a force on the bearings at the crank center, causing a reduced force to be available for the production of torque. The torque-producing force is that portion of the force perpendicular to the radius. As the crank is pushed, the torque produced is not constant; and in order to calculate the work done per revolution, an average value for torque must be found.

A graphical method can be employed in rotation to find the average torque produced. If the torque versus angular displacement is plotted, as shown in Figure 6, the area under the torque-displacement curve equals the work done. This method is used frequently in complete analysis of work done on rotating machinery.

The same effect of non-constant torque applies to hand-crank winches. Electric motors acting through gears provide a more constant source of

torque to the crank mechanism of a winch, thereby making an electric-powered winch useful in providing the smooth, constant work needed to move elevators and escalators.

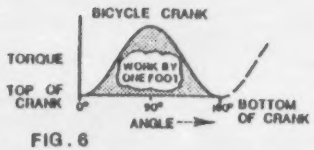


FIG. 6

SUMMARY

The winch is a mechanical device that produces rotational work through pulleys, gears, chains or other components. Some winches are designed for lift, or power applications; others, for speed. They are among the more efficient mechanical devices, finding wide and varied use.

WORK OUTPUT AND EFFICIENCY OF A WINCH

MATERIALS

Baitcasting fishing reel (similar to Shakespeare Thirfy Model 1902).
20 or more yards of nylon fishing line (20 lb-Test).
Set of metric slotted weights.
2 - Weight hangers.
Fishing rod (suggest a 2 ft crapple-rod).
Vernier caliper.
Circle cut of 1/4" plywood with a 5" diameter.
0-180, 1° protractor.
Support board with C-clamps.
2 - Meter sticks.

PROCEDURE

1. Prepare fishing reel and plywood circle, as shown in Figure 7. Drill holes to fit handle and handle nut of fishing reel. Use a rasp to make a groove around the circumference of the plywood circle.

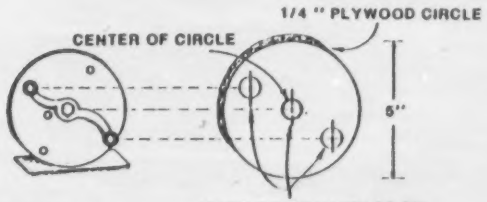


FIG. 7

2. Mount plywood circle on handle to fit, as shown in Figure 8. Wrap rubber bands around handle to hold plywood circle snug and firm.

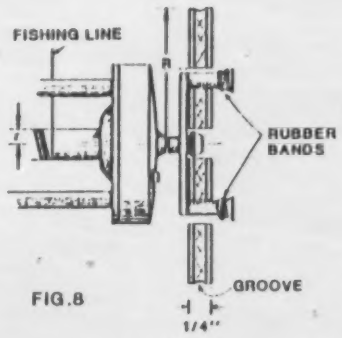


FIG.8

3. Mount fishing reel to fishing rod, and support rod and reel, as shown in Figure 9.

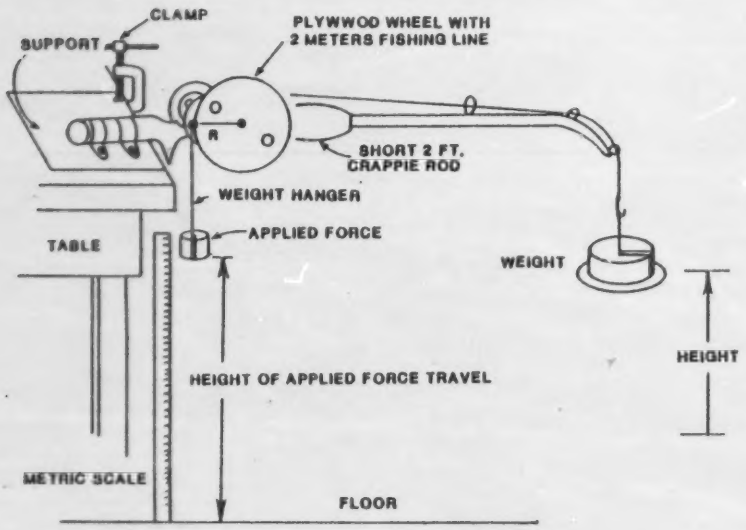


FIG. 9

4. Measure radius r of inner fishing line drum, shown in Figure 8, and measure radius of the applied force, R, shown in Figure 8. Record these radii in Data Table.

5. Place a 50 gram mass on the 50 gram mass hanger, and a 50 gram mass hanger on the line wrapped around the plywood wheel, while holding the system to prevent movement.

6. Adjust applied-force acting at edge of plywood wheel by adding masses in such a manner that system will be balanced.

7. By hand, begin motion by pulling downward slightly (to overcome friction) in order that applied-force hanger travels at approximately a constant speed. If applied-force hanger fluctuates and stops before hitting floor, add small masses to produce a smooth movement to floor.

8. Move applied force hanger up near reel, and mark on wheel where line meets plywood wheel.

9. Release hanger and observe the angular travel (i.e., complete revolutions plus fraction parts of revolution) of plywood

wheel. Record this angle in degrees in Data Table (Use protractor to measure fraction of revolution.)

10. Mark also where fishing line on reel drum meets edge of drum.

11. Record all masses on each hanger and vertical distance traveled by the 100 gram mass in Data Table.

12. After the trial, mark point at which fishing line meets drum. Measure distance along fishing line from mark-to-mark, and record in Data Table.

13. Perform work and efficiency calculations as shown in Data Table.

14. How does the efficiency of this winch compare with that of the winch in Example C?

DATA TABLE

OUTPUT WORK	INPUT WORK
Radius of line drum, r = _____ cm	Radius of APPLIED FORCE, R = _____ cm
Distance (d) from MARK-TO-MARK ON FISH LINE, _____ cm	ANGULAR TRAVEL, θ_{in} = _____ degree = _____ radians
$\theta_{out} = \frac{d}{r} = \frac{\_\_\_\_\_ cm}{cm}$ θ_{out} = _____ radian	
Mass = _____ gram (include weight hanger)	Applied Mass = _____ gram (include weight hanger)
Weight = _____ Newtons	Weight = _____ Newtons

CALCULATION RESULTS

WORK OUTPUT = [Mass x g] x r x θ_{out}

= [_____kg x 9.8 $\frac{m}{s^2}$] x _____m x _____rad

WORK OUTPUT = _____ Joule

WORK INPUT = [Mass x g] x R x θ_{in}

= [_____kg x 9.8 $\frac{m}{s^2}$] x _____m x _____rad

WORK INPUT = _____ Joule

EFFICIENCY (%) $\eta = \frac{W_{out}}{W_{in}}$ (100)

EFFICIENCY of Fishing Reel (%) = _____

SELF CHECK

1. Explain the design features of a winch, and give at least two applications.

2. A lift winch crank of 25 cm radius has a force of 100 N applied perpendicularly to the radius as it rotates through 15 revolutions. The winch drum measures 5 cm in diameter and the winch lifts 6825 N weight, rotating through one revolution. Calculate the following values:

    a) Calculate WORK INPUT to the winch.
    b) Calculate WORK OUTPUT done by the winch.
    c) Calculate efficiency of the winch.
    d) How much work is used in overcoming friction?

3. A simple hand winch designed for boat trailers has a hand crank radius of 35 cm, and a winch drum of 5 cm diameter. A 3 cm thickness of rope extends the radius of the winch drum. When a force of 50 N is applied to the crank for one revolution, find the following:

    a) How much force is applied to the boat assuming a 100% efficient winch?
    b) How much rope is taken up?

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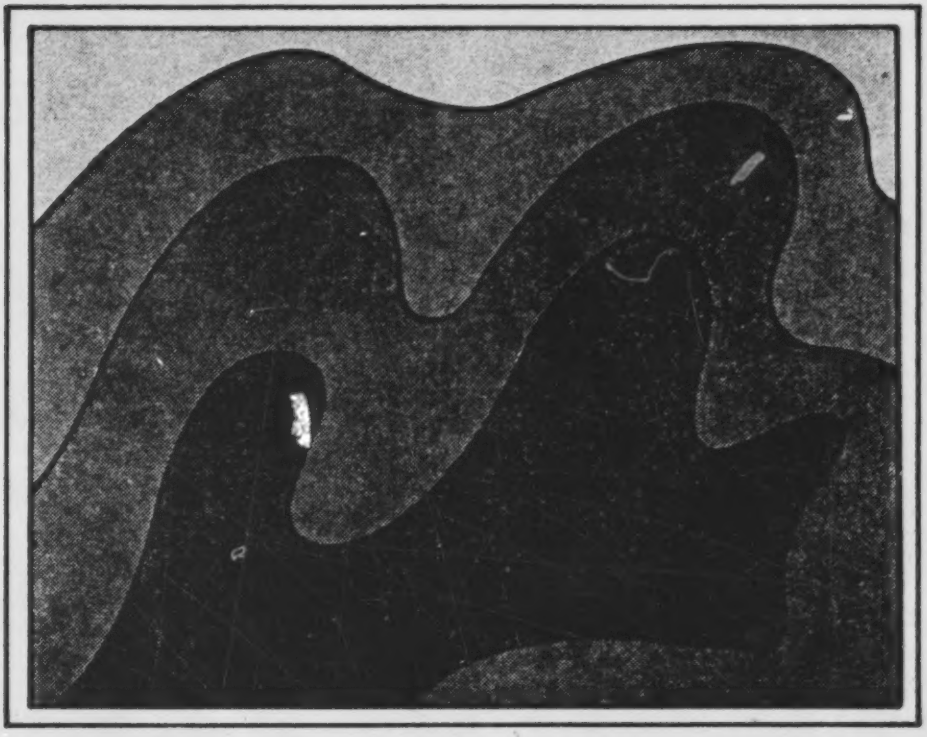
UNIFIED TECHNICAL CONCEPTS

MODULE 2 F 1

WORK DONE BY A WATER PUMP



FLUID APPLICATION OF WORK

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Energy is defined as the ability to do work. Energy also can be defined as the ability to produce action or to accomplish change. Science and technology are built upon action and change; consequently, upon energy. Today's energy shortage, caused by the limited energy resources of the earth, could limit mankind's ability to do work or accomplish change.

In this module, the student will review principles of work and energy as they apply to fluids and electricity. Values for work and energy involving fluids and electricity will be derived experimentally and in problems. In the laboratory, the student will measure current and voltage supplied to a pump, and will calculate the work and efficiency of the pump.

PREREQUISITES

Student should have completed Concept Module 2-0, "Work."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define:

  Mechanical work.
  Fluid work (done by a pump).
  Electrical work.
  Efficiency.

- Define the forcelike and displacement quantities in both fluid and electrical work system.

- Given the weight of the fluid and the height lifted, calculate the work done by a pump.

- Given the appropriate equipment, measure current and voltage supplied to a pump, and calculate the pump's work and efficiency.

In Concept Module 2-0, a general formula for work was given as shown in Equation 1.

WORK = FORCELIKE QUANTITY x DISPLACEMENTLIKE QUANTITY. (1)

Special versions of this formula were derived for mechanical, fluid and electrical systems.

FLUID WORK

In this module, the student will determine the amount of work done by a pump in lifting a quantity of water to a known height. Just as a force can be applied to a book to cause it to move across a table, a force must be applied to water to cause it to move up a tube to a greater height.

Use of Equation 1, the formula for mechanical work, makes possible the calculation of fluid work done by a pump lifting water. But in dealing with fluids, the "force" is equal to the weight of the liquid moved; and the "displacement" is the height to which the water is lifted. The mechanical work formula can be rewritten, therefore, in the form shown in Equation 2 for fluid work.

$$W = \rho_W h \qquad (2)$$

where

ρ_W = weight density in lb/ft^3.
h = height in feet.

Example A illustrates the use of Equation 1 in solving a problem.

EXAMPLE A: FLUID WORK IN LIFTING WATER

Given: 500 gallons of water are pumped to a height of 50 feet. (Recall: 1 ft^3 = 7.48 gal; 1 ft^3 = 62.4 lb.)

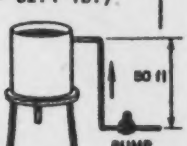
Find: Amount of work done.

Solution:

$$W = \rho_W h$$

$$= (500 \text{ gal})\left(\frac{1 \text{ ft}^3}{7.48 \text{ gal}}\right)\left(\frac{62.4 \text{ lb}}{1 \text{ ft}^3}\right)(50 \text{ ft})$$

$$= 4170 \text{ lb} \times 50 \text{ ft}$$



$W = 209{,}000 \text{ ft·lb} = 2.09 \times 10^5 \text{ ft·lb}$

Note: Since 2.09×10^5 ft·lb of work was done in lifting the water, the tank of water is now storing 2.09×10^5 ft·lb of energy in the form of potential energy.

ELECTRICAL WORK

Electrical work is defined by the formula given in Equation 3.

$$W = VQ \tag{3}$$

where
V = potential difference through which charge is moved.
Q = quantity of charge moved.

Measurement of charge moved is not always experimentally practical. However, using the definition of current, namely $I = Q/t$, charge can be defined as $Q = It$. (I = current; t = time elapsed.) This expression for "charge" in Equation 3 yields the formula shown in Equation 4 for electrical work:

$$W = VIt \tag{4}$$

where
I = current in amps.
t = time in seconds.

Potential difference, current and time are measurable quantities. Potential difference is measured by a voltmeter; current, by an ammeter; and time, by the clock. Equation 4 is used to solve a problem in Example B. Example C equates energy stored to work done.

In Examples B and C the electrical work needed to drive the pump was considerably greater than the energy stored in the water. In other words, the input work was greater than the output work. The ratio of output work to input work is called efficiency and it is usually expressed as a percentage. Efficiency can be calculated by the formula shown in Equation 5 and Example D.

$$\eta = \frac{W_{out}}{W_{in}} (100) \qquad (5)$$

where
η = % efficiency.
W_{out} = work output.
W_{in} = work input.

EXAMPLE B: ELECTRICAL WORK TO DRIVE A PUMP

Given: A water pump is connected to a 24-volt power supply for a period of 30 seconds; the current to the pump measures 10 amperes.

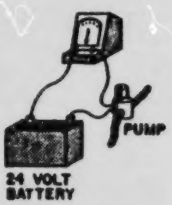
Find: Amount of electrical work done.

Solution: $W = VIt$

$= (24\ V)(10\ A)(30\ s)$

$W = 7200\ J$

7200 joules of work are needed to drive the pump.



EXAMPLE C: ENERGY STORED BY LIFTING WATER

Given: The pump in Example B lifts 50 kilograms of water to a height of 10 meters. (Recall: Weight of a 1 kg mass is 9.8 newtons.)

Find: Amount of energy stored in the water.

Solution: Energy stored = $W = \rho_w h$

$= (50\ kg)\left(\frac{9.8\ N}{1\ kg}\right)(10\ m)$

$= (490\ N)(10\ m)$

$W = 4900\ N \cdot m = 4900\ J$

4900 joules of potential energy are stored in the water because of its higher position above the reservoir.

EXAMPLE D: EFFICIENCY OF A WATER PUMP

Given: The pump described in Examples B and C.

Find: Its efficiency.

Solution:

$$\eta = \frac{W_{out}}{W_{in}} (100)$$

$$= \left(\frac{4900\ J}{7200\ J}\right)(100\%)$$

$$= (0.68)(100\%)$$

$$\eta = 68\%$$

The pump is 68% efficient. This figure indicates that 32% of the energy supplied is lost to friction in the pump and fluid resistance in the pipes.

SUMMARY

The work done by a water pump consists of the force which must be applied to water to displace it to a given height (or against other resistance). Weight density of the fluid being pumped and height to which pumped determine how much work the pump does.

PUMP WORK AND EFFICIENCY

MATERIALS

VOM (volt-ohm-milliammeter).
d.c. ammeter (0-10 amp range).
d.c. power supply.
d.c. water pump (such as Jabsco Model 12560 or equivalent).
Connecting wire.
Timer or stopwatch.
Meter sticks and metric tape.
Plastic hose to fit pump outlet.
Two bathroom scales.
Large container such as a garbage can.

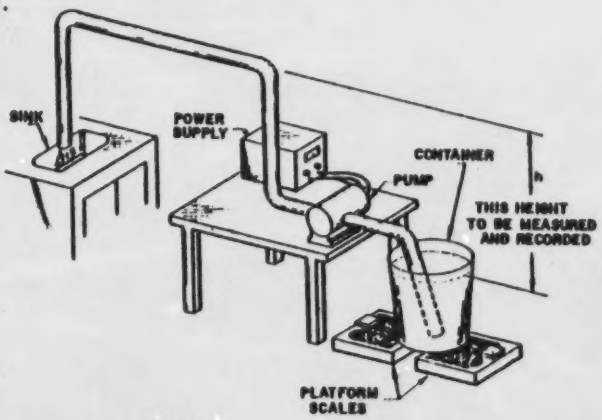


FIG. 1

PROCEDURE

1. Set up pump and other equipment as shown in Figure 1.

2. Connect all wiring as shown in Figure 2.

3. Fill container with water.

4. Turn on power supply, and adjust voltage to value listed in the Data Table for trial 1.

5. Turn off power supply, and record in Data Table total of readings on the platform scales for the start of trial.

6. Measure height from top of water in container to highest point in outlet hose (h).

7. Turn on power supply and timer simultaneously, and allow the pump to run for time specified in

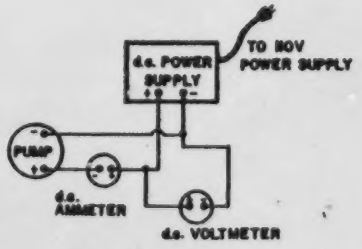


FIG. 2

the Data Table for trial 1. Measure and record in Data Table current to pump motor. Make sure pump is turned off exactly at end of specified time.

8. Record in Data Table total of readings on platform scales for the end of trial.

9. Measure height (h) from top of water remaining in the container to highest point in outlet hose. Add this to measurement taken in step 6, and divide by 2 in order to obtain an average value for the height the water is lifted. Record this average value in Data Table.

10. Refill container.

11. Repeat steps 5 through 10 for trials 2, 3 and 4.

12. Calculate input electrical work, output mechanical work and efficiency of system for each trial run, and complete Data Table.

13. How would the items calculated in step 12 change for a liquid having less density than water?

DATA TABLE

Trial	Voltage (Volts)	Current (Amps)	Time (s)	Total Scale Readings: Start of Trial (kg)	Total Scale Readings: End of Trial (kg)	Input Electrical Work* (J)	Output Mechanical Work**	% Efficiency ***
1	8		120					
2	10		120					
3	10		60					
4	10		60					

*Electrical work: $W = VIt$

**Mechanical work (fluids): $W = \rho_w h$

(Recall that 1 kg mass weighs 9.8 newtons.)

***Efficiency: $\eta = \frac{W_{out}}{W_{in}} (100)$

Height to which water is lifted _____ m

SELF CHECK

1. Define:

   Fluid work (done by a pump).
   Electrical work.
   Efficiency.

2. What are the forcelike and displacementlike quantities in fluid work?

3. What are the forcelike and displacementlike quantities in electrical work?

4. A pump operating at 24 volts while drawing 5 amps current fills a tank of 1000-gallon capacity. The water is raised 30 ft before it can be discharged into the tank. How much work is done by the pump? How much time will be required to fill the tank if the efficiency of the system is 75%?

5. A pump operating on 110 V with an efficiency of 80% lifts 200 kg of oil to a height of 40 m in 2 minutes. How much work is done? What current is required?

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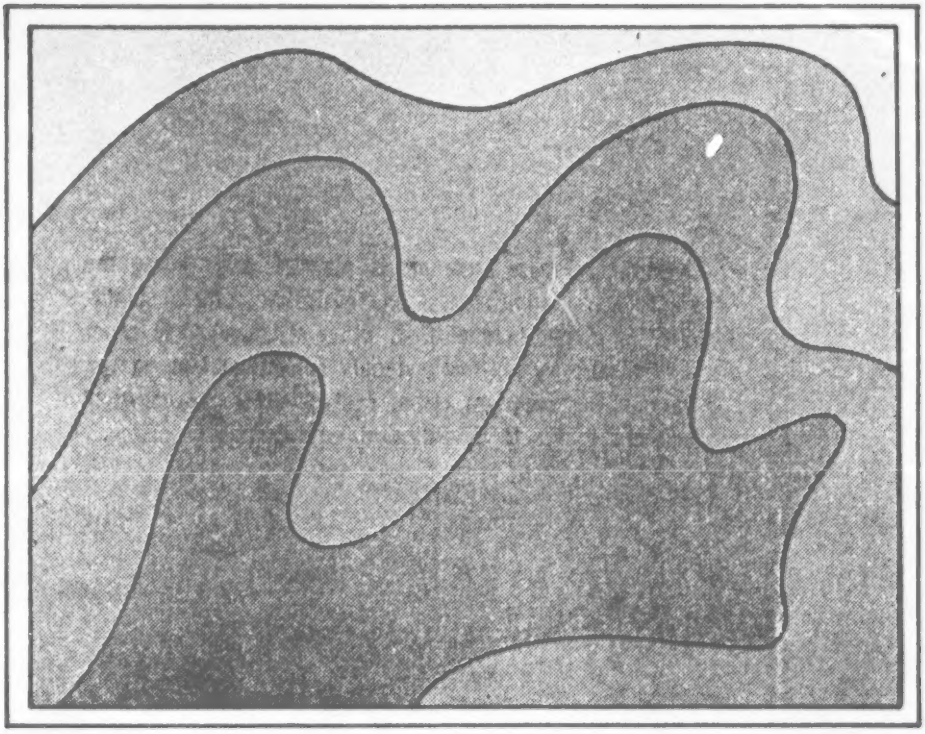
UNIFIED TECHNICAL CONCEPTS

MODULE 2 F 2

WORK DONE BY A HYDRAULIC LIFT



FLUID APPLICATION OF WORK

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

Hydraulic tools are commonly found in today's world. In the local garage, a mechanic raises a car on a hydraulic lift to get under the chassis. With a few light strokes of a lever, dentists and barbers use hydraulics to lift their chairs to a convenient working height.

In this module, work as it applies to mechanical output, work of a hydraulic lift system and work done on and by hydraulic fluids as they exert pressure within the hydraulic system of the lift are described. A hands-on procedure using a simple automotive hydraulic jack provides an opportunity to observe and calculate work done by the lift. It should be noted that the hydraulic jack is used as equipment for Modules 1F3, 2F2 and 8F1. Each of these modules addresses a different concept: force, work and force transformers, respectively.

PREREQUISITES

The student should have completed Concept Module 3-0, "Work" and should have the ability to measure distances with a vernier caliper.

OBJECTIVES

To complete this module, the student should be able to:

- Describe a hydraulic lift in two or three sentences, including a labeled diagram.
- List four hydraulic lift applications.
- Calculate output work of a hydraulic lift working against gravity, given appropriate unknowns.
- Calculate work done by fluid system in a hydraulic lift, given piston area, stroke length and fluid pressure.
- Given appropriate equipment, determine input, output work and efficiency of a hydraulic jack.

DISCUSSION

A hydraulic lift can be defined generally as a device designed to lift heavy loads. Specifically, the hydraulic lift transforms work done on its fluid system into mechanical work done against gravity to lift the heavy load. The element that accomplishes this transformation is called the hydraulic (working) cylinder. The simplest kind of hydraulic lift positions the working cylinder directly under the load, and the piston stroke of the cylinder equals distance traveled by the load. This type of lift is known as a hydraulic jack. Other hydraulic lifts apply mechanical work of the working cylinder to a system of levers to gain increased distance in which the heavy load travels. Figure 1 shows these two types of cylinder positions.

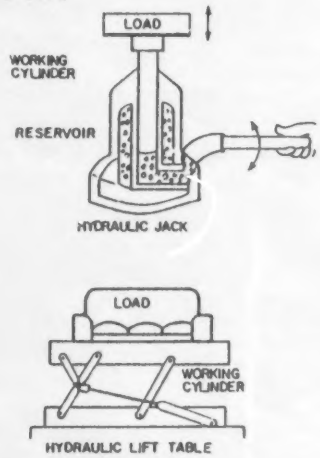


Fig. 1

Another important element of a hydraulic lift is the fluid system, which provides leverage to amplify an input force and a medium by which pressure is transmitted equally throughout. The hydraulic fluid moves through a circuit, sometimes composed of high-pressure hoses. A reservoir of fluid ensures that an adequate supply of fluid is always available. Many hydraulic lift systems contain a pump at the heart of the fluid system. The pump must maintain a high pressure in the fluid and supply changes in fluid volume. Various relief and control valves ensure that the system behaves as desired and meets safety requirements. A hydraulic tailgate lift on a truck is an example of a hydraulic lift system that incorporates all of the above mentioned elements, most of which are shown in Figure 2.

Every hydraulic lift system is powered by some source of input work. In Figure 2, an electric motor provides input work to drive the hydraulic pump. In the simple hydraulic jack lift, input work is provided by force exerted on the handle by the user.

In the case of the hydraulic car lift shown in Figure 3, input work is provided by high air pressure. The oil reservoir is pressurized and the oil valve opened to allow oil to flow under the plunger and raise the car.

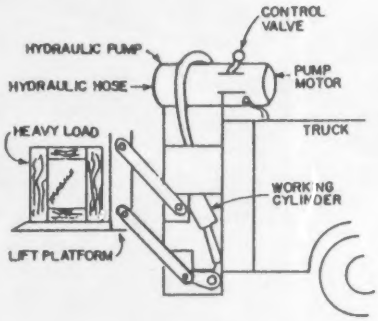


Fig. 2

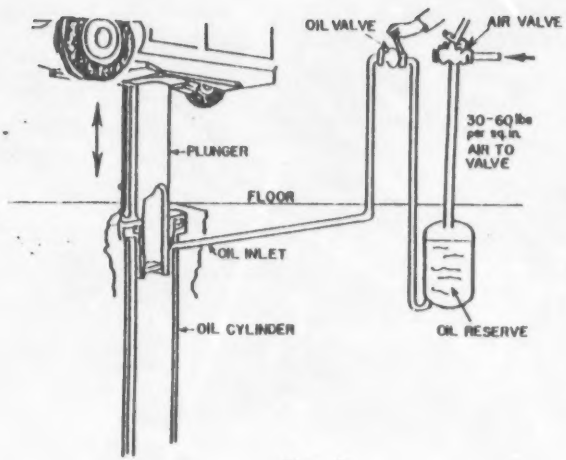


Fig. 3

HYDRAULIC LIFT OUTPUT WORK

The output work of a hydraulic lift is mechanical work done against gravity to raise a heavy load. As shown in Figure 4, direction of load weight (a gravitational force) is opposite to the displacement. The magnitude of the displacement is the height traveled by the load. Lifting force applied to the load must be at least equal to weight of the load through the travel duration.

Work done by the lift is given by Equation 1:

$$\text{Work done by hydraulic lift} = \text{load weight} \times \text{height traveled} \quad (1)$$

Example A illustrats a simple application of Equation 1.

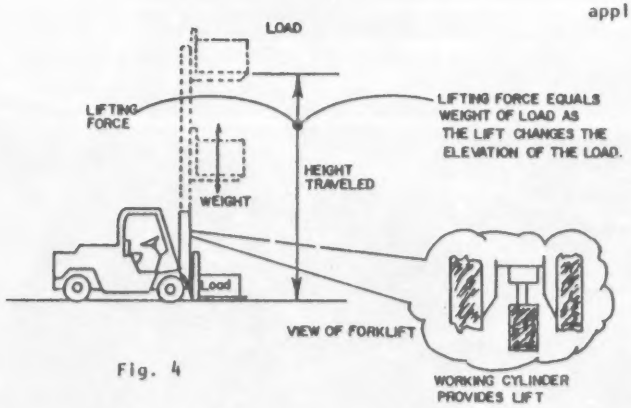


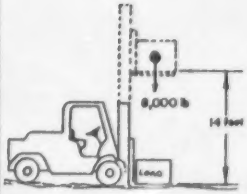
Fig. 4

EXAMPLE A: HYDRAULIC FORK LIFT WORK CALCULATION

Given: A forklift hydraulic system lifts a load weighing 8000 lb through a distance of 14 feet vertically.

Find: Output work.

Solution: Work = weight x height
= (8000 lb) x (14 ft)
Work = 112,000 ft x lb.



WORK DONE BY FLUID SYSTEM

In Concept Module 3-0, work in fluid systems was given by Equation 2:

$$\text{Work (fluids)} = \text{pressure} \times \text{volume change}.$$
$$W = P \times \Delta V. \qquad (2)$$

To illustrate this concept, a simple hydraulic cylinder is shown in Figure 5.

Fluid volume change can be determined by Equation 3:

$$\text{Fluid volume change} = (\text{cross-sectional area of piston}) \times (\text{length of piston travel}).$$
$$\Delta V = A \times L. \qquad (3)$$

Combining Equations 2 and 3, Equation 4 is obtained:

$$\text{Work done by fluid system in hydraulic cylinder} = \text{fluid pressure} \times \text{cross-sectional area of piston} \times \text{length of piston travel}.$$
$$W = P \times A \times L. \qquad (4)$$

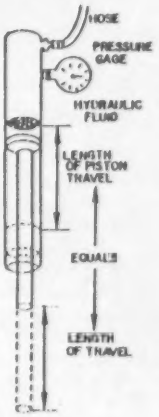
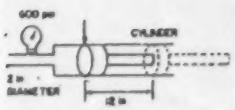


Fig. 5

Example B illustrates the use of Equation 4.



EXAMPLE B: WORK DONE IN A FLUID SYSTEM

Given: A fluid system in which fluid pressure is 600 lb/in^2, hydraulic cylinder is 2 inches in diameter and piston travels 12 inches.

Find: Work done by the fluid system.

Solution:

$$\text{Work} = \text{pressure} \times \text{piston area} \times \text{piston travel}$$

$$= (600 \text{ lb/in}^2) \times (\pi \text{ in}^2) \times (1 \text{ ft})$$

$$\text{Work} = 1885 \text{ ft} \times \text{lb}.$$

Cross-Sectional Area

$$A = \frac{\pi}{4} D^2$$

$$= \frac{\pi}{4} (2 \text{ in})^2$$

$$A = \pi \text{ in}^2.$$

In the conversion process from work done by fluid in the cylinder to output mechanical work against gravity in a lift, the process is about 97% efficient (almost all fluid work is converted to usable mechanical lifting work). Only a small percentage of energy is lost to friction. The example in Figure 6 illustrates the energy (work) in a hydraulic lift system with a mechanical energy input.

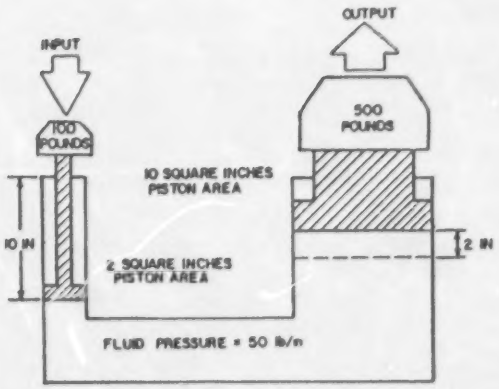


Fig. 6

Input Work	Work on Fluid by Input Piston
$W_{inp} = F_{in} \times d_{in}$ $= (100\ lb)(10\ in)$ $W_{inp} = 1000\ lb\text{-}in$	$W = PAd$ $= (50\ lb/in^2) \times (2\ in^2) \times (10\ in)$ $W = 1000\ lb\text{-}in$

Work by Fluid on Output Piston	Output Work
$W = PAd$ $= (50\ lb/in^2)(10\ in^2) \times (2\ in)$ $W = 1000\ lb\text{-}in$	$W_{out} = F_{out} \times d_{out}$ $= (500\ lb) \times (2\ in)$ $W_{out} = 1000\ lb\text{-}in$

By examination of numerical results shown in Figure 6, the statement can be made that, while force is multiplied by the lift, work done is transmitted undiminished throughout the system. The increase in force supplied by the lift is achieved at the expense of load distance moved. Note clearly that the applied force of 100 pounds must move through a distance of ten inches to lift the 500 pound load through a reduced distance of 2 inches.

MATERIALS

One hydraulic jack (1 1/2 ton or 3 ton) tapped for a pressure gage, with lever.
Pressure gage (0 - 100 psi). (Should be sufficient if suggested weights are used.)
Vernier caliper.
Metal scribe.
Set of heavy weights (1 kg, 2 kg, 5 lb).

PROCEDURE

1. Arrange experiment equipment as shown in Figure 7, making certain that weights are loaded on the output piston in such a manner that they will not fall.
2. Measure diameter of output piston with vernier caliper; record in data table.
3. Measure diameter of small input piston with vernier caliper; record in data table.
4. Place two large weights on output piston; grasp lever and press input piston down as far as it will go. Mark piston where it enters body of the jack, as shown in Figure 8. (Mark A with a metal scribe.)
5. Raise lever as far as possible; mark piston where it enters body of the jack. (Mark B in Figure 8 with metal scribe.)
6. Using vernier caliper, measure length from mark A to mark B; record this length in data table. This length is called input piston stroke travel.
7. Mark output piston where it enters and leaves the body; raise weights up through about a 6-inch distance. Count number of complete full strokes; note pressure of hydraulic fluid while raising weights.

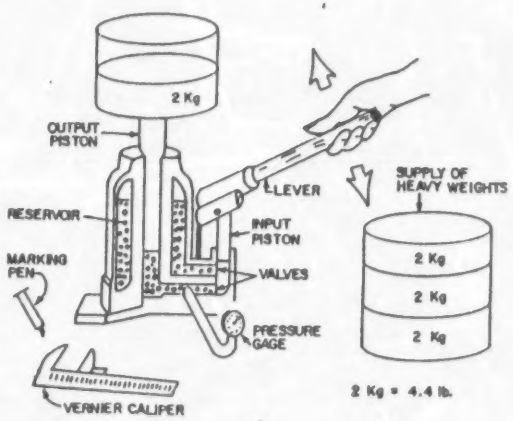


Fig. 7

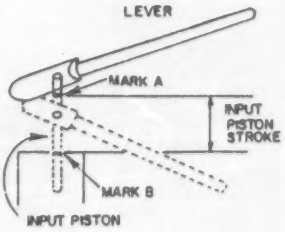


Fig. 8

Record number of strokes, fluid pressure, height that large weights were raised and value of weights (masses) raised.

8. Lower output piston to mark again; add additional load to output piston and repeat steps 4 through 7. Repeat step 8 until all rows in data table are completed.
9. Complete the data table by performing the following calculations.

$$\underset{\text{(ft-lb)}}{\text{Work output}} = \underset{\text{(lb)}}{\text{force}} \times \underset{\text{(ft)}}{\text{load travel.}}$$

$$\underset{\text{(ft-lb)}}{\text{Work done by fluid on output piston}} = \underset{\text{(lb/in}^2\text{)}}{\text{fluid pressure}} \times \underset{\text{(in}^2\text{)}}{\text{area of output piston}} \times \underset{\text{(ft)}}{\text{load travel.}}$$

$$\underset{\text{(ft-lb)}}{\text{Work done on fluid by input piston}} = \underset{\text{(lb/in}^2\text{)}}{\text{fluid pressure}} \times \underset{\text{(in}^2\text{)}}{\text{area of input piston}} \times \underset{\text{(ft)}}{\text{travel of input piston per stroke}} \times \underset{}{\text{number of strokes.}}$$

$$\underset{(\%)}{\text{Efficiency}} = \frac{\text{work output (ft-lb)}}{\text{work done by input piston (ft-lb)}} \times 100.$$

DATA TABLE
1. Output piston diameter _____ in - output piston cross-sectional area _____ in^2. ($A = \frac{\pi}{4} D^2$.)
2. Input piston diameter _____ in - input piston cross-sectional area _____ in^2.
3. Input piston travel per stroke _____ ft.

MEASUREMENTS			
Load on Output Piston (lb)	Height of Load Travel (ft)	Hydraulic Fluid Pressure (lb/in^2)	No. of Input Strokes

CALCULATION RESULTS			
Work Output (ft x lb)	Work Done by Fluid on Output Piston (ft x lb)	Work Done on Fluid by Input Piston (ft x lb)	Efficiency %

SELF CHECK

1. Draw and label a sketch of a hydraulic lift.
2. List four applications of hydraulic lifts.
3. A hydraulic jack used to lift a weight of 1200 lb a distance of 8 inches. How much work is done by the jack.
4. The input piston of the above jack has an area of 0.25 in^2 and a stroke length of 1.5 in. The fluid pressure is 692 lb/in^2 and 38 strokes are required to raise the weight. Calculate the input work.
5. Calculate the efficiency of the above jack.

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 2 T 1

HEAT ENERGY REQUIRED FOR A TEMPERATURE INCREASE

THERMAL APPLICATION OF WORK

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

Engineers and technicians need to know thermal properties of materials, such as specific heat, heat of fusion, and heat of vaporization, that are vital for heating and cooling applications. In industrial chemical processes, the necessity often arises to determine how much energy is needed to heat, cool, melt, or boil the chemical reactants. Thermal properties of materials often are measured with the aid of a device called a "calorimeter."

This module introduces the use of the calorimeter for measurement of the thermal properties of materials. In the laboratory, the student will use a calorimeter (or experimental apparatus similar to a calorimeter) to measure some thermal properties of meterials.

PREREQUISITES

Student should have completed Concept Module 2-0, "Work."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Sketch and label the eight parts of a common metallic-can calorimeter.
- Define the "water equivalent" of a calorimeter.
- Describe the use of the principle of conservation of energy used in solving calorimetry problems.
- Given six of the seven following factors, calculate the seventh:

    Mass of water in calorimeter.
    Water equivalent of calorimeter.
    Initial temperature of sample.
    Mass of sample.
    Initial temperature of water.
    Final temperature of water.
    Specific heat of sample.

- Given the mass of water in a calorimeter, the water equivalent of the calorimeter, the initial temperature and mass of a liquid sample, the specific heat of the sample as a liquid and a solid, the freezing point of the sample, and the initial and final temperature of the water, calculate the heat of fusion of the sample.

- Given the appropriate equipment, determine the specific heat of a metal sample and heat of fusion of water.

DISCUSSION

Energy is required to heat, to melt, or to boil materials. Materials differ from one another in the amount of heat required to produce a certain temperature rise and in amount of energy required to melt or to boil a specific amount of the material. These thermal properties — specific heat, heat of fusion, and heat of vaporization — have been defined in preceding modules. Knowledge of these terms is important for many scientific and engineering applications.

Measurement of these important quantities often is carried out with a device called a calorimeter. The word "calorimeter" comes from the Greek word "calor," meaning heat, and from the Latin word "meter," meaning measure. Thus, a calorimeter literally is a device for measuring heat.

There are many types of calorimeters; the most common design in a metallic can containing water. The can contains a measured quantity of water and has a cover through which a thermometer and a stirrer are inserted. An insulating jacket, or pocket of air, surrounds the can to reduce heat losses. Basic structure is sketched schematically in Figure 1.

The thermometer is used to measure temperature of the water before and after the unknown quantity of heat is introduced into the calorimeter. The amount of heat may be found from the measured rise in temperature of the water.

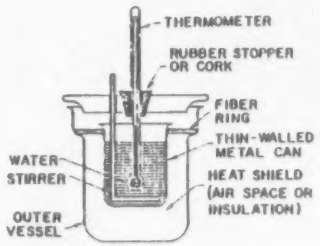

FIG. 1

MEASUREMENT OF SPECIFIC HEAT

A sample of material whose specific heat c_s is to be found is measured to have a mass m_s. Water is poured into a calorimeter, stirred, and its temperature measured. The sample is heated to a known temperature T_s and transferred into the calorimeter. When the mixture has had time for the temperature of the sample and the water to equalize, temperature of the water is measured. T_1 and T_2 are the initial and final temperatures of the water, respectively; and m_w is the mass of the water. Since the inner calorimeter can and stirrer also are heated, heat gained by calorimeter and stirrer must be included. m_c is the mass of the inner calorimeter can and stirrer, and c_c its specific heat. Assuming that no heat is lost from the calorimeter during the experiment, heat given up by the hot sample in cooling must equal heat gained by the water and by the calorimeter can. The basic equation, Equation 1, was introduced in Concept Module 2-0, "Work," and is repeated here:

$$W = mc\ (T_2 - T_1) \qquad (1)$$

where

W = thermal work.
m = mass.
c = specific heat of substance.
T_1 = initial temperature
T_2 = final temperature.

Since T_2 is the final temperature of the sample, energy given up by the sample is indicated by Equation 2.

$$H_L = m_s c_s\ (T_s - T_2) \qquad (2)$$

where

H_L = heat energy lost by sample.
m_s = mass of sample.
c_s = specific heat of sample.
T_s = temperature of sample.

Thermal energy lost by the sample is gained by the water and the calorimeter can (and stirrer). Energy gained by the water is found by use of Equation 3.

$$H_G = (m_w)(1)(T_2 - T_1) \qquad (3)$$

where

m_w = mass of water.
H_G = heat energy gained by water.
1 = specific heat of water.

Energy gained by the calorimeter can is found by use of Equation 4.

$$H_G = m_c c_c\ (T_2 - T_1) \qquad (4)$$

where

m_c = mass of calorimeter and stirrer.
c_c = specific heat of calorimeter can and stirrer.

If heat energy is to be conserved, the total energy gained by the calorimeter and water is equal to the energy lost by the sample. This equality can be stated mathematically in the form shown in Equation 5.

$$m_s c_s (T_s - T_2) = m_w (T_2 - T_1) + m_c c_c (T_2 - T_1) \qquad (5)$$

The right-hand side of the equation represents heat gained by the water and calorimeter. Heat gained by the can is equal to that gained by a mass of water equal to the product $m_c c_c$, heated through the temperature difference $T_2 - T_1$. The product $m_c c_c$, therefore, is called the "water equivalent" of the calorimeter. For many commercial calorimeters, value of the water equivalent will be specified by the manufacturer or marked on the calorimeter. The water equivalent has units of energy per unit temperature (cal/°C). If water equivalent of the calorimeter is added to the mass of water present, the calorimeter in all succeeding calculations can be ignored. When the water equivalent of a calorimeter is known, the solution of calorimeter problems is easier. Equation 5 can be rewritten in the shortened form shown as Equation 6.

$$m_s c_s (T_s - T_2) = (m_w + m_c c_c)(T_2 - T_1) \qquad (6)$$

Note that the specific heat c_s of the sample now can be determined from Equation 6, since all other quantities — namely m_s, T_s, T_2, T_1, m_w, and $m_c c_c$ — are known, or have been measured.

In a similar way, the calorimeter can be used to measure heat associated with a change of phase (melting, freezing, vaporization, or condensation) of a material. Change of phase is not accompanied by a change in temperature, but it does require energy. Changes from the solid to the liquid phase (melting) and from the liquid to the vapor phase (boiling) causes a substance to absorb energy. In reverse processes (condensing and freezing), the substance liberates energy.

Latent heat of fusion can be measured with a calorimeter when the sample is allowed to freeze. The amount of heat liberated during freezing will raise temperature of the calorimeter water by an amount measured. This relationship is given by Equation 7.

$$H_F = L_f m_s \qquad (7)$$

where

H_F = heat energy liberated by freezing.
L_f = latent heat of fusion.
m_s = mass of substance.

Energy given off by the substance during the freezing process is absorbed by the water and by the calorimeter. If water temperature increases from T_1 to T_2, the energy balance is given in Equation 8:

Heat liberated = heat absorbed

$$L_f m_s = m_w (T_2 - T_1) + m_c c_c (T_2 - T_1)$$

or

$$L_f m_s = (m_w + m_c c_c)(T_2 - T_1) \qquad (8)$$

To determine the latent heat of freezing experimentally, begin with temperature of the sample somewhat above, and end somewhat below, its freezing point. This process causes one or more additional contributions of heat energy caused by temperature change of the sample before and after freezing.

Example A combines all the above elements and illustrates how a calorimeter problem is solved.

EXAMPLE A: HEAT LOSS BY SAMPLE COOLED FROM ABOVE MELTING POINT

Given: 100-g sample of liquid lead at an initial temperature of 500°C has been inserted into a calorimeter containing 200 g of water at 5°C and having a water equivalent of 150 cal/°C. Melting point of lead is 327°C, and its heat of fusion is 5.86 cal/g. Specific heat of liquid lead is 0.035 and of solid lead is 0.031.

Find: Final temperature of the water.

Solution:

(1) Heat energy loss by the lead in cooling from 500°C to the melting point (327°C):

$$m_{\substack{\text{liquid}\\\text{lead}}} c_{\substack{\text{liquid}\\\text{lead}}} (T_2 - T_1) = (100\ \text{g})\left(0.035\ \frac{\text{cal}}{\text{g}\ ^\circ\text{C}}\right)(500^\circ\text{C} - 327^\circ\text{C})$$

$$\text{Loss (1)} = 605\ \text{cal}$$

(2) Heat energy loss by the lead while freezing (no change in temperature of lead occurs; that is, T remains at 327°C):

$$H_F = L_f m_s$$

$$= \left(5.86\ \frac{\text{cal}}{\text{g}\ ^\circ\text{C}}\right)(100\ \text{g})$$

$$\text{Loss (2)} = 586\ \text{cal}$$

(3) Heat energy loss by solid lead in cooling from the freezing point, 327°C, to the final temperature (T):

$$m_{\substack{\text{solid}\\\text{lead}}}\, c_{\substack{\text{solid}\\\text{lead}}}\, (T_2 - T_1) = (100\ g)(0.031\ \frac{cal}{g\ ^\circ C})(327 - T)$$

$$\text{Loss (3)} = (3.1\ \frac{cal}{g\ ^\circ C})(327 - T)$$

(4) Heat energy gained by water:

$$m_{water}\, c_{water}\, (T - T_1) = (200\ g)(1\ \frac{cal}{g\ ^\circ C})(T - 5^\circ C)$$

$$\text{Gained (1)} = (200\ \frac{cal}{^\circ C})(T - 5^\circ C)$$

(5) Heat gain by calorimeter:

$$(\underset{\text{equivalent}}{\text{water}})(T - T_1) = (150\ \frac{cal}{^\circ C})(T - 5^\circ C)$$

$$\text{Gained (2)} = (150\ \frac{cal}{^\circ C})(T - 5^\circ C)$$

Since heat gain must equal heat loss, these separate factors can be added together to give an energy-balanced equation.

Heat energy gain = heat energy loss

$$200\ \frac{cal}{^\circ C}\ (T - 5^\circ C) + 150\ \frac{cal}{^\circ C}\ (T - 5^\circ C) = 605\ cal + 586\ cal + 3.1\ \frac{cal}{^\circ C}(327 - T)$$

$$350\ (T - 5) = 1191 + 3.1\ (327 - T)$$

$$353.1\ T = 1191 + 1014 + 1750$$

$$= 3955$$

$$\therefore \quad T_2 = 11.2^\circ C$$

Final temperature of the water is 11.2°C.

Notice that in Example A, the final temperature T_2 was found. In actual practice, the equilibrium temperature of 11.2°C could have been measured, and the equation above used to determine latent heat for lead. (See, for example, Problem 6 in the Self Check at the end of this module.)

In Example A, specific heat was assumed to be a constant, independent of temperature. This assumption is not strictly true, because specific heat does vary slightly as temperature changes. However, at ordinary temperatures and over reasonably small temperature ranges, specific heat can be considered as constant. The error introduced by this assumption will not be great.

Another source of error involves heat exchanged between the calorimeter and the surroundings. Therefore, a quality calorimeter should be well-insulated to minimize this loss, as any heat losses

may seriously affect measurements. If possible to arrange the experiment in such a manner that initial temperature of the water in the calorimeter is slightly below that of the surroundings, and the final temperature slightly above, this error can be reduced. In such a case, the heat lost to, and gained from, the surroundings will tend to cancel out.

SUMMARY

An accurate determination of the heat energy necessary to raise the temperature of a body a certain amount requires that the mass and specific heat of the body be known. The specific heat of a substance can be determined experimentally with a calorimeter. Careful procedures and measurements are required, and the heat energy transferred to the calorimeter also must be accounted for. Calorimeters also can be used to determine the latent heat of a material.

DETERMINATION OF SPECIFIC HEAT OF METAL SAMPLE

MATERIALS

Water calorimeter. (An acceptable calorimeter can be made from styrofoam cups or from other materials.)
Thermometer.
Balance.
Samples of copper and aluminum. (Other metals can be substituted.)
Ice.
Bunsen burner and ring stand with wire gage; or hot plate.
Beaker.
Tongs (insulated jaws).

PROCEDURE

1. Determine mass of a small quantity of water, m_w, with a balance. Record in Data Table 1. Pour water into a calorimeter.

2. Determine and record mass (m_s) of metal sample with balance. Immerse metal sample in a beaker of water; heat it on hot plate until water has boiled. Measure and record this temperature (T_s). At the same time, stir and measure temperature T_1 of water in the calorimeter. With tongs, quickly remove metal from boiling-water bath and insert it into calorimeter. Be careful not to transfer water with metal. Stir thoroughly; allow time for temperature to come to equilibrium. Measure and record final temperature T_2 of water in calorimeter.

3. From measurements taken, calculate specific heat, using formula in Equation 5. If a commercial calorimeter is used, use manufacturer's stated water equivalent of the calorimeter. If a home-made calorimeter, from a can of known metal, is used, weigh can, and use a table of specific heats to determine water equivalent. (Table 4 in Concept Module 2-0 lists specific heats of several common metals.)

4. When the specific heat of metal has been determined, compare results to tabulated value (Table 4 of Module 2-0). Complete Data Table 1. Discuss possible sources of error with instructor.

5. Repeat Steps 1 through 4 with other sample provided.

MEASUREMENT OF HEAT OF FUSION OF ICE

MATERIALS

Same materials as in first procedure.

PROCEDURE

1. Measure mass m_w of a small quantity of water; pour into calorimeter.

2. From an ice-water bath (a well-stirred mixture of water and ice at 0°C), dip out a piece of ice, dry it with a paper towel. Mass m_i of ice dipped out may be determined later by weighing entire calorimeter can containing original water and melted ice. Record in Data Table 2 the temperature of water (T_1) in calorimeter just before adding ice.

3. Drop piece of ice into calorimeter, and stir until all ice melts. (If all ice does not melt, start again with somewhat warmer water in calorimeter.)

4. Measure and record final (minimum) temperature T_2.

5. Reweigh calorimeter can to determine mass of ice added; record ice mass.

6. Calculate heat of fusion using Equation 8, adding a factor that takes into account the increase in temperature of mass of melted ice following melting process. The equation becomes —

$$L_f m_i + m_i\ (1)(T_2 - 0°C) = (m_w + m_c c_c)(T_1 - T_2).$$

Two terms on left side of the equation will be amount of energy required to melt ice and then raise melted ice to final temperature T_2. Note that, on the right side $(T_1 - T_2)$ is used, since final temperature T_2 is lower than initial temperature T_1.

7. Compare heat of fusion of water determined here with known value of 80 calories per gram. Complete Data Table 2. Discuss possible sources of error in this experiment with instructor.

DATA TABLE 1								
Sample	m_w	m_s	T_s (Sample)	T_1	T_2	c_s (Calculated)	c_s (Standard)	% Error
1 _____								
2 _____								

DATA TABLE 2							
m_w	m_i (Ice)	T (Ice)	T_1	T_2	L_f (Calculated)	L_f (Standard)	% Error
		0°C				80 $\frac{cal}{g}$	

SELF CHECK

1. Describe the construction of a calorimeter; sketch and label its parts.

2. Define "water equivalent" of a calorimeter.

3. Describe how to use a calorimeter to measure the following quantities:

   Specific heat.
   Heat of fusion.

4. Show how Equations 5 or 6 and 8 demonstrate that energy is conserved, in this case, heat energy.

5. Suppose that one adds a piece of aluminum weighing 100 g and heated to a temperature of 180°C to a water calorimeter containing 200 g of water at 10°C and with a water equivalent of 152 cal/deg. What will be the final temperature of the well-stirred mixture? (Specific heat of aluminum is 0.22 cal/g-C°.)

6. Suppose that one drops some liquid gallium metal (which melts near 30°C) at a temperature of 50°C and a weight of 100 g into a water calorimeter containing 100 g of water at 5°C. After the mixture is stirred, final temperature is 20°C, and the gallium metal has solidified. The water equivalent of the calorimeter is 46.35 cal/deg. Specific heat of the liquid gallium is 0.0954, and that of solid gallium is 0.0895 cal/g-C°. What is the latent heat of fusion of gallium metal? (Remember to include separate contributions for cooling of liquid gallium, heat of fusion, and cooling of solid gallium.)

7. What is the water equivalent of a steel calorimeter weighing 100 g? (Use Table 4 of Concept Module 2-0.)

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UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 2 T 2

HEAT ENERGY REQUIRED FOR MELTING

THERMAL APPLICATION OF WORK

Technical Education Research Center – Southwest

TERC – SW

INTRODUCTION

Matter exists as a solid, liquid or gas. Under certain conditions, the state of matter may change. Boiling of water and melting of ice are examples of change of phase of matter. In this module, energy required to change from a solid to a liquid state while temperature remains constant is examined. This energy is called the heat of fusion. The student will experimentally measure heat of fusion of water in the laboratory.

PREREQUISITES

Student should have completed Concept Module 3-0, "Work."

OBJECTIVES

To complete this module, the student should be able to:

- Define:
  - Heat of fusion.
  - Supercooled liquid.
  - Crystalline solid.
- Given heat of fusion of a material, calculate heat energy necessary to change a known mass of that material from a solid to a liquid.
- Given the appropriate equipment assemble the apparatus and demonstrate the process for measuring the heat of fusion of water.

DISCUSSION

This module will discuss change of phase of matter from solid to liquid or liquid to solid. Consider the types of materials for which this phase change is valid.

Figure 1 shows the arrangement of molecules in a crystalline solid. This is a material in which positions of the molecules form a regular, predictable matrix. Each type of crystalline solid has its own characteristic matrix. When this type of material is heated, the molecules vibrate about their fixed positions. Expansion of the material occurs as vibrations force the average distance between molecules to increase slightly. When sufficient heat energy is added to the solid, it will begin to melt. This occurs when forces of vibrational motion exceed the forces that hold the molecules in place. Structure of the resulting liquid is shown in Figure 2.

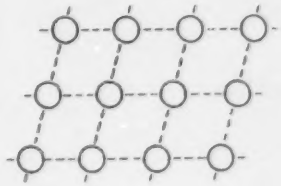

Fig. 1

Molecules of a liquid are free to move throughout the liquid. They have vibrational energy just as they had in the crystalline solid; they also have kinetic energy associated with their random motion. The phase change investigated is this transition between crystalline solid and liquid.

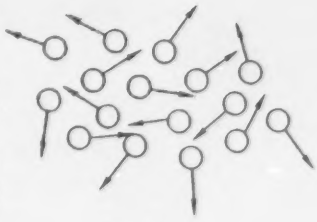

Fig. 2

Not all solid materials have the crystalline structure discussed above. Supercooled liquids are materials such as glass and pitch that exhibit most of the characteristics of solids but lack a regular crystalline structure. Their internal structure is always that of a liquid, and they do not undergo a change of phase as they pass from solid to liquid form. There is no precise melting point as there is for a crystalline solid. Viscosity of the supercooled liquid decreases slowly as temperature increases. Such materials do not exhibit a heat of fusion.

Other materials for which heat of fusion has no meaning are those in which chemical changes occur upon heating. Many organic solids fall into this category.

The heat of fusion of a material is the quantity of heat energy per unit of mass that must be supplied to that material at its melting point to convert it completely to a liquid at the same temperature. Figure 3 shows the temperature of a sample of water as heat energy is added. Initially, the water is frozen and has a temperature below 0° C. As heat is added, the water's temperature increases until

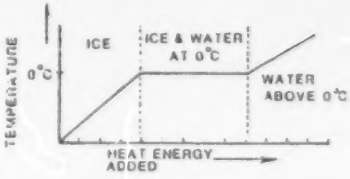

Fig. 3

it reached 0° C and ice begins to melt. Temperature then remains constant until all the ice has melted into water. Heat energy added in this section of the chart causes a change of state in the water but does not raise its temperature. When all the ice has melted, added heat then causes a further temperature increase.

Normal melting point is the temperature at which a solid melts when heat is applied to it at atmospheric pressure. Table I gives normal melting point and heat of fusion of several materials.

TABLE I: NORMAL MELTING POINT AND HEAT OF FUSION OF SUBSTANCES

Substance	Normal Melting Point		Heat of Fusion cal/g
	°K	°C	
Helium	3.5	-269.65	1.25
Nitrogen	63.18	-209.97	6.09
Oxygen	54.36	-218.79	3.3v
Ethyl alcohol	159	-114	24.9
Mercury	234	-39	2.82
Water	273.15	0.00	79.7
Lead	600.5	327.3	5.86
Silver	1233.95	960.80	21.1
Gold	1336.15	1063.00	15.4

Equation I is used to determine heat energy necessary to melt a given mass of a substance.

Heat energy required = mass of substance x heat of fusion. (1)

In symbols: $Q = mL$.

Example A shows use of this equation in solving a problem.

The same equation (1) may be used to determine the amount of heat energy that must be removed to cause a given amount of liquid at the melting point to form a crystalline solid. Example B shows this.

EXAMPLE A: SOLID-TO-LIQUID ENERGY CALCULATION

Given: 2 kg of ice.

Find: Amount of heat energy necessary to melt the ice.

Solution:

$Q = mL$
$= (200\ g)(79.7\ cal/g)$
$Q = 159{,}400\ cal.$

EXAMPLE B: LIQUID-TO-SOLID ENERGY CALCULATION

Given: 250 g of liquid mercury at 15° C.

Find: Amount of heat that must be removed to transform it into solid mercury at the same temperature.

Solution:

$Q = mL$
$= (250\ g)(2.82\ cal/g)$
$Q = 705\ cal.$

Example C is a slightly more complex problem, similar to the one that must be solved in the experimental portion of this module.

EXAMPLE C: TIME FACTOR CALCULATION IN A FUSION PROBLEM

Given: An electrical heating element delivers 250 watts of electrical power used to melt 480 g of ice.

Find: How long it will take to melt all the ice at 0° C.

Solution:

$Q = mL$
$= (480\ g)(79.7\ cal/g)$
$= 38{,}256\ cal$
$= (38{,}256\ cal) \times (4.186\ J/cal)$
$Q = 1.60 \times 10^5\ J.$

Calculate total heat energy required.

$t = Q/P$
$= (1.60 \times 10^5\ J) \div (250\ W)$
$= 640.5\ s$
$t = 10\ min\ 40.5\ s.$

1 watt = $\frac{1\ joule}{second}$

MATERIALS

Low-voltage high-current d.c. power supply.
Voltmeter.
Ammeter.
Centigrade thermometer.
Coil of resistance wire (resistance must be compatible with d.c. power supply).
Ice cubes.
Water.
Calorimeter.
Lab timer or watch with second hand.
Laboratory balance.

PROCEDURE

1. Fill a calorimeter cup about half full of water; add several ice cubes. Allow it to sit until ice-water mixture has reached a constant temperature of 0° C. (Some ice must be present.)
2. Make electrical connections; set up apparatus completely as shown in Figure 4.
3. Use laboratory balance; determine mass of several ice cubes at 0° C to be added to calorimeter. Dry carefully; weigh quickly; add cubes immediately to calorimeter cup. Note: Just before adding dry, weighed cubes to ice-water mixture at 0° C, spoon out whatever ice is still in original mixture. Failure to do this will result in erroneous results.

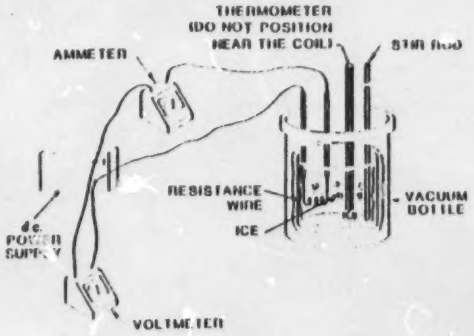

Fig. 4

4. As soon as cubes are added to calorimeter cup, turn on d.c. power supply; start lab timer. Record constant voltage and current produced by power supply. Do not use a high rate of heating.
5. Stir ice-water mixture constantly; watch temperature. It may be necessary to remove cover of calorimeter periodically to determine when added ice cubes have melted.

6. When all ice has melted (and temperature still reads 0° C), record total run time of power supply; complete data table.

DATA TABLE
Mass of dry ice cubes added: m = _____ g.
Voltage of power supply: V = _____ volts.
Current of power supply: I = _____ amperes.
Run time of power supply: t = _____ s.
Electrical power delivered: P = IV
= _____ amp x _____ volts
= _____ watts.
Total energy delivered: E = Pt
= _____ watts x _____ s
= _____ joules.
Heat energy delivered: Q = E (joules) ÷ (4.186 J/cal)
= _____ joules ÷ 4.186 J/cal
= _____ cal.
Heat of fusion of water: L = Q/m
= _____ cal ÷ _____ g
= _____ cal/g.

SELF CHECK

1. Define the following terms:
   Heat of fusion.
   Supercooled liquid.
   Crystalline solid.
2. How much heat energy is required to change 2.5 kg of lead from a solid to a liquid at 327.3° C?
3. How much heat energy must be removed from 500 g of water at 0° C to change it to ice at 0° C?

REFERENCES

Sears, F.W. and Zemansky, M.W. Modern College Physics, Part I: Mechanics and Thermodynamics. Reading, MA: Addison-Wesley Publishing Co., 1962.

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UNIFIED TECHNICAL CONCEPTS

MODULE 2 T 3

HEAT ENERGY REQUIRED FOR BOILING

THERMAL APPLICATION OF WORK

Technical Education Research Center - Southwest TERC - SW

INTRODUCTION

Energy is required to change water at 100° C (the normal boiling point of water) to steam at 100° C. This energy is called the heat of vaporization. For water, the heat of vaporization is 539 cal/g. This value is considerably higher than the energy needed to raise the same mass of water from 0° C to 100° C.

In this module, the temperature of water as it is heated to boiling will be measured as a function of time and the effect of the heat of vaporization noted. Effect of the heat of vaporization in providing cooling as a liquid evaporates will be described, and methods for measuring the heat of vaporization of water by condensing steam in a water bath will be shown.

PREREQUISITES

Student should have completed Concept Module 3-0, "Work and Energy" and Application Module 3T1, "Heat of Fusion."

OBJECTIVES

To complete this module, the student should be able to:

- In two or three sentences, define heat of vaporization and change of phase.
- List two physical processes that contribute to the energy requirements for phase change in boiling fluids.
- Given the formula and appropriate variables, calculate heat of vaporization for a specified material.
- Describe three methods of measuring heat of vaporization:
  - Continuous flow.
  - Steam calorimeter.
  - Electrical heating methods.
- Given necessary equipment, measure the heat of vaporization of water.

- In one or two sentences, compare caloric requirements for the heat of vaporization, heat of fusion and heat needed to raise a given mass of water from 0° to 100° C.

DISCUSSION

A definite amount of heat (or energy) is required to vaporize a unit mass of liquid. This amount of heat is called the heat of vaporization and varies in value from one liquid to another. The term "phase" relates to the fact that matter can exist as a solid, liquid or gas. Evaporation of a liquid is an example of change of phase from a liquid to a gas.

The word phase is used to describe which of these possible forms the material is in. Thus water can exist in solid form as ice, in liquid form as water and in gaseous form as steam. Most materials can exist in any of these three forms or phases under the proper conditions of temperature and pressure. Materials that are solid at ordinary temperatures (e.g., lead) can be melted and then boiled as the temperature increases. Materials usually consider to be gases (e.g., oxygen) can be reduced to a liquid and then frozen as temperature is decreased. Some chemical compounds will break down instead of melting or vaporizing and thus do not exist in each of the three possible phases.

The transition between the three possible forms is called a change of phase. Thus melting, freezing, boiling and condensation are all examples of changes of phase. The change between the solid and liquid phase and the energy required for this change (heat of fusion) is discussed in Module 3T1.

Energy is required to change a liquid into a vapor. In other words, when a liquid boils, energy in the form of heat is required to accomplish the change. The amount of energy needed per unit mass is called heat of vaporization. Sometimes the terms "latent heat of vaporization" is used.

Boiling of water in a beaker is shown schematically in Figure 1, with bubbles of steam rising in the water and with clouds of steam rising above the surface. Heat required to produce the change from water to steam is being supplied by the flame below the water. Water will be used frequently as an example. However the general concept of heat of vaporization is applicable to most liquids.

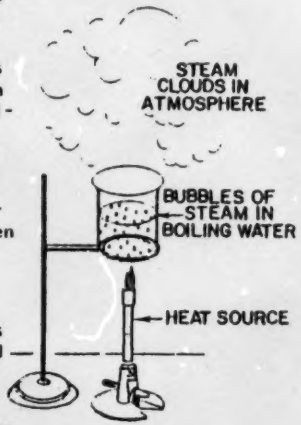

Fig. 1

Two important physical processes that contribute to the energy requirements are:

Energy needed to separate a molecule from the attractive forces of the other molecules in the liquid.
Energy used in expanding the vapor against the surrounding atmosphere.

The attraction of the molecules is illustrated in Figure 2. Here a molecule (very simply represented by the circle) escapes from a liquid surface in spite of the attraction of other molec-

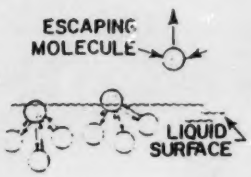

Fig. 2

ulars in the liquid. As energy is supplied, motion of the molecule increases and its attraction to other molecules weakens as they move farther apart until, finally, it can escape from the surface.

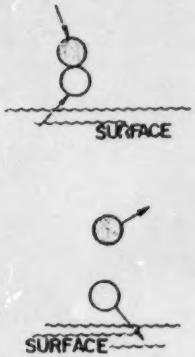

Fig. 3

Even after escaping from the surface, the molecule can be reflected back to the surface by collisions with molecules in the surrounding atmosphere (Figure 3). The top part of the figure shows a molecule from the atmosphere (solid circle) colliding with a molecule that has escaped from the liquid (open circle). The lower part of the figure shows the escaped molecule being driven back into the surface.

Thus, the heat of vaporization can be considered to arise from two factors - energy needed to overcome the attractive forces holding the liquid together and energy needed to expand the vapor against the surrounding atmosphere.

Because of the effect of the surrounding atmosphere, it is easier to boil a liquid when the pressure is lower. Thus water boils at a lower temperature when the atmospheric pressure is lowered. The boiling temperature of water will be found to decrease in traveling from sea level into the mountains. Example A illustrates this effect.

Heat of vaporization, again, is the energy required to boil a unit mass of a liquid and is the energy needed to change the material from liquid at the boiling point to vapor, still at the boiling temperature. Thus, the phase change with its associated energy is accomplished without an increase in temperature.

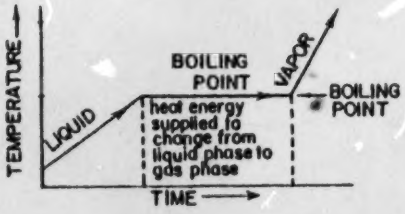

Fig. 4

Figure 4 shows the temperature of a liquid as it is heated through the boiling point. At the left edge, the material is liquid at a temperature below the boiling point. As heat is supplied, temperature increases, until the boiling point is reached. Temperature stops increasing as boiling proceeds. The heat supplied is the heat of vaporization and is used to change the phase from liquid to gas. The temperature remains constant, at the boiling point, until all the liquid has boiled. When all the liquid has boiled, temperature increases again, as heat is now supplied to the vapor.

If the vapor is cooled, it can be condensed back into liquid. Energy is released during the phase change from vapor to liquid. This energy is called "heat of condensation." Heat of condensation is numerically equal to heat of vaporization.

EXAMPLE A: CALCULATION OF BOILING ENERGY

Given: 539 cal/g is needed to boil water at 100° C and 1 atm pressure. (Density of steam under these conditions is 0.000555 g/cm³.)

Find: Energy needed to push back the surrounding air. How much energy was needed to overcome attractive forces?

Solution: Work done by expansion against the atmosphere is:

$$W_{exp} = p\,(V_2 - V_1)$$

where

V_1 = volume of 1 g water = 1 cm³/g.
V_2 = volume of 1 g steam = 1/(0.000555 g/cm³) = 1802 cm³/g.
p = 1 atmosphere pressure = 1.013×10^6 dyne/cm².

Therefore:

$$W_{exp} = (1.013 \times 10^6)\ \frac{\text{dyne}}{\text{cm}^2}\ (1802 - 1)\ \frac{\text{cm}^3}{\text{g}} = 1.82 \times 10^9\ \frac{\text{erg}}{\text{g}}$$

Converting energy in ergs to energy in calories,

$$W_{exp} = 1.82 \times 10^9\ \frac{\text{erg}}{\text{g}} \times \frac{\text{joule}}{10^7\ \text{erg}} \times \frac{0.239\ \text{cal}}{\text{joule}} = 43.5\ \frac{\text{cal}}{\text{g}}$$

The remainder of the work is used to overcome the molecular attraction:

$$W_{mol} = W - W_{exp} = \frac{539\ \text{cal}}{\text{g}} - \frac{43.5\ \text{cal}}{\text{g}} = \frac{495.5\ \text{cal}}{\text{g}}$$

Thus, 92% (495.5 cal) of the heat of vaporization overcomes forces of molecular attraction, while the remaining 8% (43.5 cal) does the necessary work of expansion.

Recall: Work in a fluid system.

1 erg = dyne-cm.

Table I shows values for the heat of vaporization for several different materials. Normal boiling points are also given. (Normal boiling point is the temperature at which liquid boils when the pressure is one atmosphere.) Notice that units for heat of vaporization are energy per unit mass, e.g., calories/gram.

The heat of vaporization is a function of the atmospheric pressure, because energy is needed for the escaping vapors to move into the surrounding atmosphere, as described. The values quoted in Table I are relevant to evaporation only at a pressure of 1 atmosphere.

TABLE 1. HEATS OF VAPORIZATION FOR COMMON MATERIALS (AT NORMAL BOILING POINT)		
Material	Normal Boiling Point (°C)	Heat of Vaporization @ 1 Atmosphere Pressure (cal/g)
Oxygen	-183	51
Nitrogen	-196	48
Water	100	539
Benzene	80	93
Acetone	56	125
Mercury	357	71
Lead	445	78

The heat of vaporization is a function of atmospheric pressure because energy is needed for the escaping vapors to move into the surrounding atmosphere, as described. Heat of vaporization also depends on the temperature at which vaporization occurs. Liquids can evaporate at temperatures below their normal boiling point. Thus, an open dish of water evaporates slowly, even though the water is at room temperature. Values in Table 1 are relevant to evaporation at the normal boiling point of each material. In Table 2, data are presented for the heat of vaporization of water at various temperatures. It is not surprising that heat of vaporization decreases as temperature increases.

TABLE 2. HEAT OF VAPORIZATION OF WATER AT VARIOUS TEMPERATURES	
Temperature (°C)	Heat of Vaporization (cal/g)
0	596
50	570
100	533
200	462
300	331

The heat of vaporization of water is surprisingly high. Energy needed to melt a gram of ice and raise it to normal boiling point is only about 1/3 as much as the energy to change that same gram of water to steam. Shown in Figure 5 is a comparison of heats of fusion and vaporization for water, and also of heat needed to raise water from 0° to 100°C. The extra energy possessed by steam indicates that burns caused by steam can be very severe.

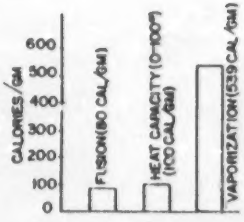

Fig. 5

Emphasis is made that the heat of vaporization is thermal energy, as described in Module 3-0. The total amount of energy required for the change of a given mass of liquid to vapor is given by the equation:

$$\text{Energy} = \text{mass} \times \text{heat of vaporization.}$$
$$H = mL_v. \qquad (1)$$

Because heat must be supplied to evaporate liquids, it should be clear that evaporating liquids can be used as a cooling process. The heat of vaporization is extracted from, and so cools the surroundings. Thus a person with a fever is rubbed with alcohol to help keep body temperature down. As the alcohol evaporates, the heat required is drawn from the person's body, thereby cooling him or her. Likewise, the evaporation of perspiration is an important method of body temperature regulation (Example B).

In hot, desert driving conditions, canvas bags are often seen on the front of a car. Some water evaporates through the canvas, and resulting cooling helps keep the car from overheating. Evaporative coolers on tops of houses have been an important method of cooling homes in the southwestern United States for many years.

The above examples all involve evaporation of a liquid below its normal boiling point. Boiling liquids also have important applications in cooling. Energy for the heat of vaporization is extracted from the surroundings and keeps the surrounding material cold. Boiling liquid nitrogen keeps infrared detectors at a temperature of -196° C. Boiling water is used to cool some types of nuclear reactors.

MEASURING HEAT OF VAPORIZATION

Heat of vaporization may be measured by several techniques. The most common techniques will now be described in turn.

EXAMPLE B: CALCULATION OF TEMPERATURES DURING EVAPORATION

Given: 1.5 g of water placed in a dish that weighs 300 g and has a specific heat of 0.4 cal/g x °C. The initial temperature is 25° C, and the water evaporates, taking all its heat of vaporization from the dish.

Find: Final temperature of the dish.

Solution: Heat required to evaporate the water is 583 cal/g x 1.5 g = 874.5 cal. The heat supplied by the dish is:

$$300 \times 0.4 \times (25 - T_f)$$

where T_f is the final temperature.

Because the heat of evaporation is supplied by the dish,

$$300 \times 0.4 \times (25 - T_f) = 874.5$$
$$25 - T_f = 874.5/(300 \times 0.4) = 7.3$$
$$T_f = 25 - 7.3 = 17.7° \text{ C}.$$

The process of evaporation cools the dish from 25° C to 17.7° C.

Interpolate between 0° and 50° in Table 2.

Recall: $H = mc\Delta t$.

METHOD OF MIXTURES (STEAM CALORIMETER)

When two materials at different temperatures are placed in contact, heat is transferred from the hotter one to the colder one until the temperatures are equalized. If heat loss to the surroundings is negligible, the amount of heat gained by the colder material equals the amount of heat lost by the hotter material. Usually at least one of the materials is a liquid, to minimize loss to the environment. Mixing takes place in a "steam calorimeter," which provides insulation from the environment. Heat gained or given up may include contributions from heat of vaporization, heat of fusion, and specific heats.

The method involves measurement of the masses of the two materials and the initial and final temperatures. One then equates all the heat quantities released by parts of the mixture to all the heat quantities absorbed by parts of the system. This is necessary if energy is conserved in the process. When all the other quantities are known or measured, an unknown heat of vaporization can be obtained. Use of this method in calorimeters is described more fully in Module 3T6. Examples C

and D demonstrate how the method of mixtures is applied with respect to heat of vaporization.

EXAMPLE C: HEAT OF VAPORIZATION FROM METHOD OF MIXTURES

Given: 40 g of steam at 100° C forced into 1000 g of water at 30° C. The final temperature of the water is 53.4° C.

Find: Heat of vaporization of water.

Solution: Heat is liberated in two steps:

Heat liberated by steam in condensing = mL_v = 40 L_v

Heat liberated by condensed steam (now a liquid) in cooling below 100°C
= $mc\Delta t$
= (40)(1)(100 - 53.4)
= 1864 calories.

Heat is absorbed by the original mass of water in warming to the final temperature:

Heat absorbed = $mc\Delta t$ = (1000)(1)(53.4 - 30) = 23,400 calories

as

Heat liberated = heat absorbed
40 L_v + 1864 = 23,400
40 L_v = 21,536
L_v = 538 cal/g.

The experimental data lead to a reasonably good value for the heat of vaporization of water.

CONTINOUS FLOW METHOD

Heat of condensation liberated by the material being studied is transmitted to a stream of water flowing at a constant rate. Increase in the temperature of the water is measured. This is essentially a steady state method. Vapor is condensed to liquid continuously, and the mass of liquid condensed per unit time is measured. The rate at which heat is liberated must be equal to the rate at which the flowing water is absorbing heat. Thus if M grams of the material are condensing in unit time, and M_w grams of water are undergoing a fixed temperature increase in the same time, it must follow that:

EXAMPLE D: HEAT OF VAPORIZATION FROM METHOD OF MIXTURES

Given: 30 g of steam at 100° C admitted to 500 g of ice at 0° C. At equilibrium it is found that 239.5 g of ice have melted.

Find: Heat of vaporization of water.

Solution: Heat is liberated in two steps:

Heat liberated by steam in condensing = $mL_v = 30\ L_v$

Heat liberated by steam in cooling to the final temperature of the ice-water mixture, which is 0° C = $mc\Delta t = (30)(1)(100)$ = 3000 cal.

Heat is absorbed only by the melting of part of the ice. Recall that the heat of fusion of ice is 80 cal/g.

Heat absorbed by ice in melting = $mL_f = (239.5)(80)$ = 19,160 cal

as

Heat liberated = heat absorbed

$30\ L_v + 3000 = 19{,}160$

$30\ L_v = 16{,}160$

$L_v = 538.7$ cal/g.

The experimental data yields a good value for the heat of vaporization of water.

$$MH = M_w\ (T_f - T_i)\ C_w \qquad (3)$$

where

C_w = specific heat of water (1 cal/g x °C).

$T_f - T_i$ = change in temperature of water.

H = heat of condensation.

ELECTRICAL HEATING METHOD

If electrical energy is supplied at a known rate P, and temperature of the liquid is measured as a function of time, a curve is obtained similar to that shown in Figure 4. When the liquid begins to boil, the graph becomes horizontal. Once boiling begins, it must be true that the rate of electrical energy input P must be the same as the rate at which the heat of

vaporization boils off the liquid. If m grams of the liquid boil per second:

$$mH = P. \qquad (5)$$

As the other quantities may be determined by straightforward measurements, the heat of vaporization H may be obtained directly.

MEASUREMENT OF TEMPERATURE VERSUS TIME DURING BOILING

MATERIALS

Bunsen burner.
Two beakers, one of which fits inside the other (Figure 6).
Thermometer.
Stopwatch.
Water.
Ethylene glycol (available as commercial permanent antifreeze).
Stone.
Stand to hold beakers.

PROCEDURE

1. Set up apparatus as shown in Figure 6. Inner beaker should contain plain water. Outer beaker should be filled with a mixture of 50% water and 50% ethylene glycol. Mixture in outer beaker has a boiling temperature higher than that of water. Put a stone in bottom of inner beaker, to keep this beaker from floating when empty.
2. Begin heating with bunsen burner. Start stopwatch when heating begins.
3. Stir mixture in outer beaker thoroughly to equalize temperature. Record temperature at various values of time, as measured on stopwatch. Take temperature measurements as water in inner beaker boils. When water in inner beaker has all boiled away, make a few more temperature measurements in outer beaker. Turn off bunsen burner before mixture in outer beaker starts to boil.
4. Plot data on a sheet of graph paper (Figure 7) giving temperature versus time. Compare result to Figure 4. Explain why plot has form that it does.

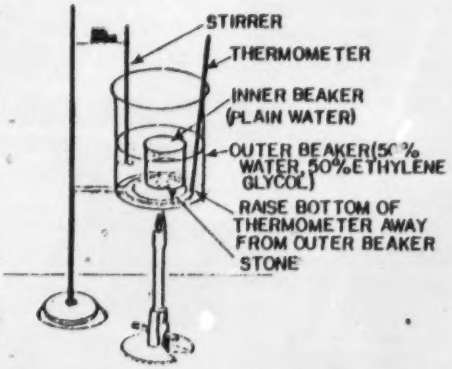

Fig. 6

COOLING EFFECT OF AN EVAPORATING LIQUID

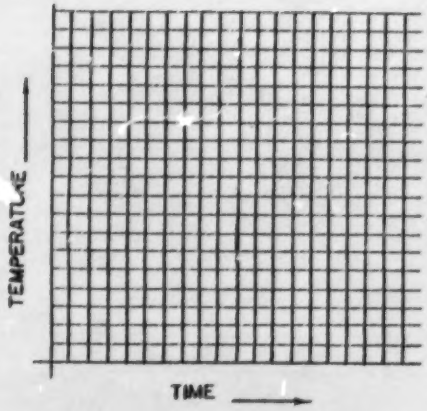

Fig. 7

MATERIALS

Rubbing alcohol.

PROCEDURE

1. Moisten wrists with a small amount of rubbing alcohol.
2. What sensation is observed? Explain why this is felt.

MEASUREMENT OF HEAT OF VAPORIZATION OF WATER

MATERIALS

Bunsen burner.
Distillation apparatus - completely assembled sets are available from chemical supply houses; otherwise one can be constructed from a flask, rubber stoppers, outlet tube and coil condenser.
Scale.

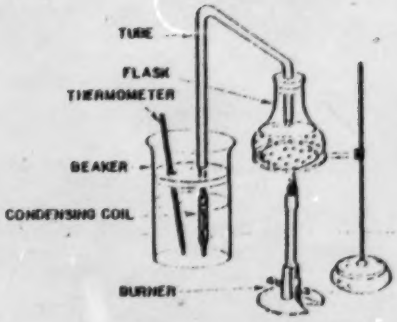

Fig. 8

PROCEDURE

1. Set up distillation apparatus, with flask held over bunsen burner. Figure 8 shows a possible improvised arrangement (one of many possible configurations) in which end of condensing coil is stopped with a rubber stopper and coil is immersed in a beaker of water.
2. Weigh empty condensing coil on scale. Weigh empty beaker. Add water to beaker; weigh again.
3. Hook up condensing coil to outlet tube; insert in beaker so that it is immersed in water. Use thermometer to measure water temperature.

4. Fill flask with water; begin heating flask with bunsen burner.
5. Allow some water to boil and recondense in coil. Stir water in beaker with thermometer; observe temperature readings. When temperature of water in beaker has risen perceptibly, measure final temperature. Turn off heat.
6. Weigh condensing coil, with condensed steam in it.
7. Fill in data table. Calculate heat of vaporization (equal to heat of condensation) for water from Equation 6. List possible sources of difference from value in Table 1.

$$L = \frac{1}{m_s}\left[m_w c_w (T_f - T_i) + m_b c_b (T_f - T_i) - m_s c_w (100 - T_f)\right]. \quad (6)$$

DATA TABLE			
1.	Mass of empty coil	_____	g.
2.	Mass of empty beaker: m_b	_____	g.
3.	Mass of beaker plus water	_____	g.
4.	Mass of water (3 - 2): m_w	_____	g.
5.	Initial temperature of water: T_i	_____	°C.
6.	Mass of coil with condensed water	_____	g.
7.	Mass of condensed steam (6 - 1): m_s	_____	g.
8.	Final temperature: T_f	_____	°C.
9.	Specific heat of beaker c_b (look up value for glass)	_____	cal/g x °C.
10.	Specific heat of water c_w	1.0	cal/g x °C.
11.	Heat of vaporization L (from Equation 6)	_____	cal/g.

SELF CHECK

1. Define in a short paragraph, heat of vaporization, change of phase and heat of condensation.

2. Describe the two principal physical processes involved in the phase change from liquid to vapor.
3. Discuss three methods to measure heat of vaporization.
4. Compare the heat of vaporization per gram of water to the heat of fusion per gram of water and to the heat needed to raise one gram of water from 0° to 100° C.
5. Ethyl alcohol is boiled at its normal boiling point of 78° C. It requires 10,200 calories to change 50 grams from liquid at 78° C to vapor at 78° C. What is the heat of vaporization of ethyl alcohol?

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Gray, D.E., ed. American Institute of Physics Handbook. 3rd ed. New York: McGraw-Hill, 1972. See especially Section 4j.

Sears, Francis Weston. An Introduction to Thermodynamics. Cambridge, MA: Addison-Wesley Publishing Co., 1953. See especially Chapter 6.

UTC

UNIFIED TECHNICAL CONCEPTS

MODULE 2 T 4

FUNDAMENTALS OF AIR CONDITIONING

THERMAL APPLICATION OF WORK

Technical Education Research Center - Southwest

TERC - SW

INTRODUCTION

The process of cooling an object or an area is accomplished by work, which removes heat from either. Heat is energy; therefore, heating and cooling basically are processes of moving energy from one place to another. Fans, pumps and motors are used to move energy through a system. If a fan is placed in a window and used to pull warm air from the house, while another window fan pulls in cooler evening air to replace it, the fans are moving heat energy. When a fan is directed at somebody, that person experiences a cooling effect, since evaporation of body moisture carries away excess body heat. More complex systems that are capable of moving larger quantities of heat energy have been constructed, creating the air-conditioning or refrigeration effects. This module introduces the basic principles of air conditioning, including energy and cost efficiency. In the laboratory, the student will determine energy and cost efficiency, and will measure temperature of an air-conditioning system.

PREREQUISITES

Student should have completed Concept Module 2-0, "Work."

OBJECTIVES

Upon completion of this module, the student should be able to:

- Define the following terms:

  Calorie.
  Kilocalorie.
  Btu.
  Mechanical equivalent of heat.
  EER (energy efficiency ratio).
  Btu/h.

- Determine the EER (energy efficiency ratio) of an air conditioning unit, given the Btu/h and watts input.

- Given the necessary data, calculate the cost difference per day of air conditioners with different EERs.
- Draw a schematic diagram, illustrating the parts of an air conditioning unit; and describe the temperature and pressure changes that take place within the system.
- Given the appropriate equipment, determine cost and energy efficiency of an air-conditioning unit, and measure temperatures of an air-conditioning system.

DISCUSSION

Heat (energy) applied to a body causes the temperature of the body to rise. In fact, this relationship is how the basic unit of heat is defined. There are three common units in use today for measuring heat energy:

The Calorie.
The Kilocalorie.
The British thermal unit (Btu).

The heat unit most commonly used in refrigeration and air conditioning theory is the Btu, which is the quantity of heat that must be supplied to one pound of water to raise its temperature one degree Fahrenheit (Figure 1).

A calorie is the quantity of heat required to raise 1 gram of water through one Celsius degree; therefore, a kilocalorie is the quantity of heat required to raise 1 kilogram of water through one Celsius degree.

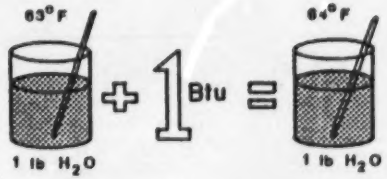

FIG. 1

In all three of these definitions, heat itself is not directly observed; rather, the change (temperature) that it produces. The conversion between units is given by the following relations:

1 kilocalorie = 1000 calories.
1 Btu = 252 cal = 0.252 kilocalorie.

Before mechanical refrigeration was invented, ice was used to refrigerate. A ton of ice melting in 24 hours absorbs heat at the rate of 12,000 Btu per hour. This figure has carried over into the field of mechanical refrigeration in such a manner that a refrigeration system which removes heat at the rate of 12,000 Btu per hour is said to have a capacity of "one ton." The Btu rating of an air conditioner needed to cool a house of a given size can be calculated as shown in Example A.

Energy in mechanical systems usually is expressed in ft·lbs, ergs or joules. Energy in the form of heat is expressed in calories or Btu's. The relative magnitudes of the "mechanical units" and the "heat units" of energy are known quite accurately and are given as follows:

1 Btu = 778 ft·lb.
1 calorie = 4.186 joules.
1 kilocalorie = 4186 joules.

EXAMPLE A: CONVERTING TON CAPACITY TO BTU'S	
Given:	A 2700 ft^2 home, for which there is an estimated requirement for a 5-ton air-conditioning unit.
Find:	The number of Btu per hour (Btu/h) removed from the home by this system.
Solution:	$H\ (Btu/h) = Tonnage \times \frac{12{,}000\ Btu/h}{1\ ton}$ $= 5\ ton \times \frac{12{,}000\ Btu/h}{1\ ton}$ $H\ (Btu/h) = 60{,}000\ Btu/h$

These relations are often expressed in ratio form, and are called "the mechanical equivalent of heat." Thus, 4.186 joules/calorie or 778 ft·lb/Btu are mechanical equivalents of heat.

Mechanical cooling by use of an air conditioner may seem complex; however, the process is merely an application of several principles that already should have been studied. These principles can be summarized in a series of four statements, which should be kept in mind as the functioning of an air conditioner is described. They are as follows:

- As a gas is compressed, its temperature increases.
- Removing sufficient heat energy from a gas causes it to liquefy.
- A liquid under pressure boils at a higher temperature.
- Boiling liquids absorb energy (heat).

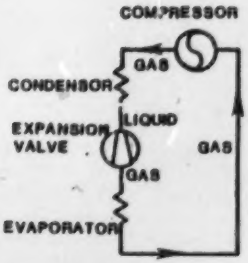

FIG. 2

Freon-12 is a gas vapor at room temperature and pressure. Many air-conditioning systems use this gas or a similar one. Freon is put into an air-conditioning system at a certain pressure. The continual change of the freon back and forth between its gas and liquid phases forms the basis for the air-conditioning system. Figure 2 illustrates the changing state of freon through the air conditioner. A detailed explanation follows.

Freon is introduced into a system and maintained there at a minimum pressure of about 70 psi. The freon starts at the compressor (Figure 2) at about room temperature and at 70 psi. Figure 3 shows that the compressor increases the pressure of the freon in the system. As a result of the increased pressure, there also is an increase in gas temperature. At 200 psi, freon turns to a liquid

at about 110°F. Since the gas is now at about 140°F, it will liquefy if cooled by 30 degrees. Liquefaction will be the next step in the process.

The gas is passed through the condenser coils, which function like an automobile radiator. A fan draws outside air past the coils, removing heat from the hot, circulating gas. The freon thus is cooled sufficiently to liquefy (Figure 4).

When liquid freon reaches the expansion valve, it is allowed to drop in pressure to about 70 psi. The lower pressure allows the liquid freon to boil as it rushes into the evaporator coils. The evaporator, acting as a "reverse radiator," supplies the heat energy needed for the freon to boil or vaporize. Necessary heat is supplied by the warm room air as it passes over the evaporator. The air passing over the evaporator is cooled (Figure 5) and is circulated back into the room to lower the ambient temperature.

The gaseous freon now is returned to the compressor, and the cycle repeats itself. Figure 6 summarizes the entire system.

The efficiency of air conditioners becomes increasingly important because of dwindling energy supplies and increasing costs. The energy efficiency ratio (EER) of a central air-conditioning unit is an important factor that determines cost of operation. The energy efficiency ratio measures the amount of cooling an air-conditioning system accomplishes per watt of electricity used. It is arrived at by dividing the Btu/h capacity by the wattage input. The more efficiently an air conditioner operates, the less electricity it uses, and the more money and energy are saved.

The EER of several air conditioning systems are listed in Figure 7.

FIG. 3

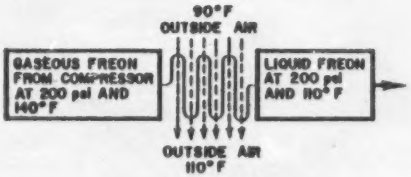

FIG. 4

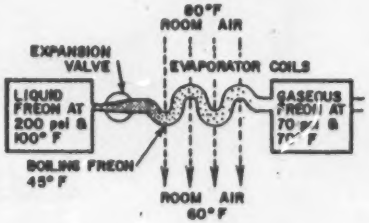
80°F ROOM AIR
EXPANSION VALVE
EVAPORATOR COILS
LIQUID FREON AT 200 psi & 100° F
GASEOUS FREON AT 70 psi & 7[illegible] F
BOILING FREON 45° F
ROOM AIR 60° F

FIG. 5

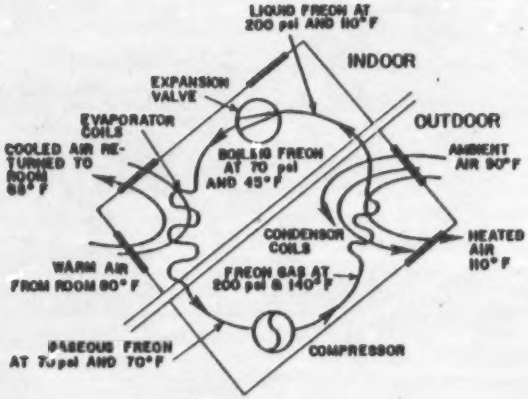
LIQUID FREON AT
200 psi AND 110°F
INDOOR
EXPANSION
VALVE
EVAPORATOR
COILS
OUTDOOR
COOLED AIR RE-
TURNED TO
ROOM
65°F
BOILING FREON
AT 70 psi
AND 45°F
AMBIENT
AIR 90°F
CONDENSOR
COILS
HEATED
AIR
110°F
WARM AIR
FROM ROOM 80°F
FREON GAS AT
200 psi @ 140°F
GASEOUS FREON
AT 70psi AND 70°F
COMPRESSOR

FIG 6

Sears
Our lowest priced central air units with
our top efficiency ratings*
Special
Purchase
$529
24,500 BTUh condensing unit, A coil.
Tubing, thermostat, installation, extra
THERE'S WHY YOU SAVE
All systems rated in accordance with Air Conditioning
and Refrigeration Institute Standard 210-75.
Ask about Sears Credit Plans

FIG 7

EER and cost-effectiveness calculations for specific units are shown in Example B.

EXAMPLE B: COMPARING UNITS WITH DIFFERENT EER'S

Given: An air-conditioning system with an EER of 10 as compared to a system with an EER of 5.

Find: The amount of money saved, using this system.

Solution: Assume that 30,000 Btu/h are to be removed from the house by either unit.

$$EER = \frac{Btu/h}{wattage} = 10$$ (Consider the more efficient system first.)

$$Wattage = \frac{Btu/hr}{10} = \frac{30,000}{10} = 3000\ W \text{ or } 3.0 \text{ kilowatts}$$

If electricity costs 7¢ per kilowatthour, and if the system is run continuously 24 hours per day, the cost for one day's use of this system would be as follows:

$$Cost = 3.0 \text{ kilowatts} \times 24 \text{ hours} \times \frac{7¢}{\text{kilowatthour}}$$

$$= \$5.04 \text{ per day}$$

$$EER = \frac{Btu/h}{wattage} = 5$$ (Consider the less efficient system next.)

$$Wattage = \frac{30,000}{5} = 6000 \text{ watts} = 6 \text{ kilowatts}$$

$$Cost = 6 \text{ kilowatts} \times 24 \text{ hours} \times \frac{7¢}{\text{kilowatthour}}$$

$$= \$10.08 \text{ day}$$

If the EER is doubled, the efficiency is doubled; and the costs are then cut in half.

SUMMARY

Through mechanical work, the air conditioner produces a temperature difference that results in the cooling of objects or areas. Freon (or similar gas) is compressed by the compressor and is vaporized at the expansion valve, at which point cooling results.

COST AND ENERGY EFFICIENCY OF AN AIR CONDITIONER

MATERIALS

Air conditioning unit or system.
Electrical and thermal specifications for the air conditioning system.

PROCEDURE

1. From an installed air conditioner or a manufacturer's specification sheet, obtain the following published information:

   Power consumption _____ watts.

   Cooling capacity (H) _____ Btu/h.

   Energy efficiency ratio _____ (EER).

   Note: The information on an installed unit is located on a metal plate located on the housing of the outside compressor unit.

2. Calculate the EER of the unit by dividing the cooling capacity in Btu/h by the power consumption:

$$EER = \frac{Btu/h}{wattage}$$

   Compare this value to the published EER rating.

3. From an air conditioning dealer, obtain the following information:

   Installed cost of several air conditioning units with different EERs.
   Average operating cost (utility bills) per year for each unit.

4. Calculate the total cost over 10 years for each unit according to this formula: Total cost = cost of unit + 10 x (annual

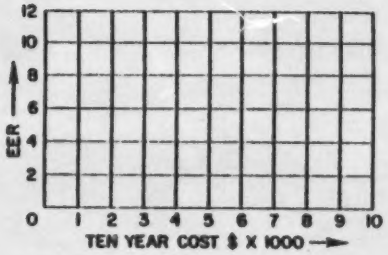

FIG. 8

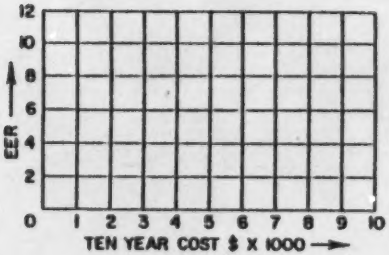

FIG. 9

operating cost). Plot this data as a function of EER (Figure 8).

5. Which air conditioner (EER) is more economical to own?

6. Repeat step 4, assuming that the cost of electrical power has doubled. Plot the data as a function of EER (Figure 9).

7. Under this condition, which air conditioner is more economical to own?

MEASURING TEMPERATURES OF AN AIR-CONDITIONING SYSTEM

MATERIALS

Contact thermometer (thermocouple).
Air conditioning unit or system.
Electrical and thermal specifications for the air conditioning system.
Graph paper.

PROCEDURE

Note: This procedure should be considered optional (at the discretion of the instructor), since it can only be performed at certain times of the year.

1. Use standard mercury thermometer to measure air temperature at the following locations in or near operating air conditioner:

   Inside a building at return-air register.
   Inside a building at cool-air outlet to a room.
   Ambient temperature of outside air.
   Temperature of outside air as it leaves condenser coils (while fan is blowing).

2. If possible, measure temperature of two copper pipes containing freon at point outside the building where they enter compressor unit. (Use contact thermocouple thermometer.)

   - The cooler pipe is carrying freon entering compressor.
   - The hotter pipe is carrying freon leaving condenser.

3. Record data from steps 1 and 2. Compre these six temperature readings to the typical values shown in Figure 6.

DATA TABLE						
Tempera-tures °F	Warm Air From Room	Cooled Air Returned To Room	Outside Ambient Air	Outside Hot Air From Condenser	Freon Entering Condenser	Freon Leaving Condenser
From Figure 6						
Measured value						

SELF CHECK

1. Define the terms:

   Calorie.
   Kilocalorie.
   Btu.
   Mechanical equivalent of heat.
   EER.
   Btu/h.

2. Determine the EER from a specification plate on a window air conditioner listing the following information:

   18,000 Btu/h.
   220 V.
   2250 watts.

3. Calculate the 24-hour cost of each of these air conditioners with the following specifications: (electricity cost 6¢/kilowatthour)

   12,500 Btu/h, 1559 watts.
   18,000 Btu/h, 2250 watts.
   24,000 Btu/h, 2665 watts.

4. Draw a schematic diagram illustrating the parts of an air-conditioning unit, and describe the temperature and pressure changes that take place within the system.

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